2015

Performance Assessment and Evaluation of Hydrophobic and Ultraviolet Protective Treatments for Historic Log Structures

Courtney Magill
University of Pennsylvania

Performance Assessment and Evaluation of Hydrophobic and Ultraviolet Protective Treatments for Historic Log Structures

Abstract

This thesis focuses on the evaluation of the durability of traditional and modern sustainable hydrophobic and ultraviolet (UV) resistant treatments for historic log structures such as those found at the Bar BC Dude Ranch in Grand Teton National Park, WY. These treatments are evaluated on a variety of criteria including performance in accelerated weathering, ecological sustainability, and impact on aesthetic and heritage character. Like many log structures in the American West, Grand Teton National Park's historic structures are exposed to a large amount of UV radiation. In addition to problems delineated from contact with water, the physical fabric of wood is damaged by UV light through degradation of lignin. Exposed wooden members are often affected by this damage in a matter of days. The small depth of penetration restricts damage to surface area. However, when combined with shrinkage and swelling of water sorption or abrasion from weathering, surface material delaminates, exposing untreated surfaces for further delignification and loss of fabric.

Accelerated weathering was conducted using a QUV Weatherometer in the Architectural Conservation Laboratory (ACL) which simulates weathering by subjecting samples to cycles of UV-B light, heat, condensation, and sprayed water. While artificial weathering occurs in more intense, concentrated cycles than those in nature, results can be a good indicator of the longer-term performance of the treatments. Five modern and two historically-used treatments were chosen for testing on samples of lodgepole pine (Pinus contorta latifolia), a common building material in the area, obtained from a supplier in the region. Samples were monitored every 100 hours to observe surface degradation and were then evaluated pre- and post-weathering using microscopic analysis, Fourier Transform Infrared Spectroscopy (FTIR), contact angle measurements, and color measurements with a spectrophotometer. Supplementary natural weathering will be conducted on site this summer in order to verify lab results, and the combined results of the lab and field testing programs will inform the Park's conservation and maintenance program for the many historic log structures in their care. This testing was performed in cooperation with the National Park Service (NPS) and the Western Center for Historic Preservation (WCHP).

Keywords

wood, conservation, accelerated weathering, ultraviolet, NPS

Disciplines

Architectural Engineering | Architectural Technology | Historic Preservation and Conservation

Comments

Suggested Citation:

Magill, Courtney (2015). *Performance Assessment and Evaluation of Hydrophobic and Ultraviolet Protective Treatments for Historic Log Structures*. (Masters Thesis). University of Pennsylvania, Philadelphia, PA.

PERFORMANCE ASSESSMENT AND EVALUATION OF HYDROPHOBIC AND ULTRAVIOLET PROTECTIVE TREATMENTS FOR HISTORIC LOG STRUCTURES

Courtney Llewellyn Magill

A THESIS

In

Historic Preservation

Presented to the Faculties of the University of Pennsylvania in
Partial fulfillment of the Requirements of the Degree of

MASTER OF SCIENCE IN HISTORIC PRESERVATION

2015

____
Advisor
Frank Matero
Professor of Architecture, Historic Preservation

____
Program Chair
Randall F. Mason
Associate Professor of City and Regional Planning, Historic Preservation

For my family. You have always encouraged me to pursue my dreams. Thank you for your neverending support.

Acknowledgements

I would like to express my gratitude to my advisor, Frank G. Matero, for first introducing me to the wonderful architecture of Grand Teton National Park and for his guidance and support throughout this thesis process.

Thank you so much to my reader, John Fidler, for his keen interest in this project and for patiently helping me to research wood coatings and formulate this experiment.

To the staff of the Western Center for Historic Preservation and the National Park Service, especially Katherine (Longfield) Wonson, Alan Williams, and Ben Isaacson, thank you for introducing me to the site and helping me facilitate shipping log samples across the country.

Thank you to Beth A. Price of the Philadelphia Museum of Art for spending a late Friday evening with me in the lab analyzing wood samples.

To the faculty and staff of the Historic Preservation Department of the University of Pennsylvania, I have enjoyed learning so much from you over the past two years. Special thanks to John Hinchman for tossing around ideas with me and helping prepare my samples, to Andrew Fearon for his guidance and passion for wood preservation, to Reza Vatankhah for his advice and assistance with analysis, and to Amanda Bloomfield and Suzanne Hyndman for always being so sweet and wonderful.

Finally, thank you to my friends, family, and loved ones. You have kept me sane through this process with all of your encouragement and love. Words cannot express how much I appreciate you.

Table of Contents

List of Figures

List of Tables

Chapter 1: Introduction

This thesis examines the durability of historical-traditional and modern clear and lightly tinted protective treatments for historic log structures. These treatments have been conducted on recently felled, old-growth forest samples of the western species Lodgepole pine (*Pinus contorta latifola*), a coniferous softwood species used widely in historic construction throughout the Rocky Mountain region. After artificial weathering, the coatings have been assessed primarily on their hydrophobic and UV-resistant qualities and secondarily on aesthetic appearance in an effort to make recommendations for use in the preservation and maintenance of log structures found in northwestern Wyoming, focusing on historic sites found in the National Parks. Testing has been run in cooperation with the Western Center for Historic Preservation, based in Moose, Wyoming.

This research focuses on preservative surface treatments for wood that are hydrophobic or UV resistant rather than biocidal. Preservative treatments for wood derive from four basic methods: pretreatment of wooden members before installation in the structure, usually by impregnation with substances such as CCA (copper, chrome, arsenic) or borates; biocidal washes; one-time biocidal treatments delivered during repairs, such as pentachlorophenol; and relatively short-lived[1] protective systems of paints, stains and coatings. The treatments selected for this research consist of this last method of treatment, striving for increased protection through durable protective surfaces. Thus, it addresses treatments that can be applied to largely prevent the conditions conducive to wood decay rather than treat those symptoms that can occur once decay conditions have been reached. However, most finishes do require some sort

[1] Most coating systems require regular maintenance every few years to retain their effectiveness. Even for treatments that claim to have a long life (i.e. 5-10 years), the coatings should be monitored to ensure product retention and continued protection of the wood substrate.

of fungicide to prevent the formation of mildew on the surface. Wood has a hydrophilic character due to the hydroxyl groups contained in its structure; these hydroxyl groups allow for the movement of water along with other nutrients throughout the body of the tree. However, once these wood cells die, excess of water can create a climate of decay. Thus, hydrophobic treatments can be especially significant in wood conservation due to the detrimental effects that extensive water absorption can have on the material, for wood is only safe from decay when kept dry. At moisture contents above the fiber saturation point, usually around 18%, various agents of decay such as fungi, insects, and water-soluble impurities can begin to degrade the material. The speed of attack of organisms depends on various combinations of moisture content, temperature, relative humidity, and different chemicals present in the wood. Most of these decay agents cannot tolerate moisture levels below 18%, some as low as 8%. Thus, prevention of moisture content higher than this level can be an effective way to limit wood decay (Ridout 2000, 23-24).

Ultraviolet (UV) light can also damage the physical fabric of wooden surfaces through degradation of lignin in the material. This photo-oxidation leads to colored decomposition products that results in the lightening or darkening of the wood surface, depending on the species. This process can happen rather quickly, affecting the exposed wooden member in a matter of days. Due to a small depth of penetration however, this damage is restricted to surface areas up to approximately 400-700 µm deep in softwoods. The depth of penetration, however, depends on spectral characteristics of the light source, the duration of exposure, the density of the wood substrate, its chemical components, and the orientation of the wood grain (Rowell 2012, 172). Though depth of penetration is usually shallow, when combined with the shrinkage and swelling of water sorption or abrasion from weathering, surface material can begin to delaminate, exposing untreated surfaces for further delignification (Ridout 2000,32).

Additionally, coatings that do not protect against UV radiation can also face accelerated polymer degradation from the release of free radicals in the wood caused by substrate surface breakdown, causing them to be rendered ineffective. In the field, it is important that coatings have as long of a life as possible, even under harsh weathering conditions, because often historic structures, especially largely disused ones, can receive preservation attention only sporadically over their lifetimes. It is vital to note that decay in wooden members can occur due to a variety of factors inherent to the substrate. The degree of decay in certain conditions can be affected by the species of tree, the type of that species (hardwood or softwood), the density of the ring structure in the wood substrate (slow growth or fast growth)[2], the portion of the tree the member was cut from (heartwood or sapwood), and the natural resins, gums, and extractives found in the wood which may promote water-repellence or fungicidal qualities (Ridout 2000, 3-15).

Treatments to prevent decay in wood have been developed in various cultures over thousands of years; however, most of these require regular applications over the lifetime of the structure for proper maintenance.[3] Many historic structures have suffered due to a lack of continued maintenance programs, and some treatments such as lead pastes or the Madison Formula are no longer available due to health and safety restrictions. In an effort to preserve these wooden structures, synthetic treatments have been developed that have varying levels of efficacy both in durability, appearance, and other preservation standards. Moreover, the characteristic appearance many traditional surface treatments impart to wood need to be

---

[2] Trees that have grown slowly have tighter growth rings and consequently denser fabric, making them more resistant to water penetration.

[3] The frequency of reapplication of coatings depends on the product and the conditions of the site. Some film-forming coatings like paints require that the old material is removed before application of a new layer while other treatments, such as pine tar resin, benefit from layering new coatings on top of older treatments.

considered, especially in association with other interventions such as replacement wooden members. Evaluating some of the widely-used modern treatments for these qualities as compared to their historic predecessors can help preservationists understand the long-term effects of treatments as well as the maintenance needed to keep them effective.

Primary testing focuses on the performance of both traditional and the newer synthetic products as measured by accelerated weathering using a QUV Panel Weatherometer at the Architectural Conservation Laboratory/UPenn. A Weatherometer simulates accelerated weathering by subjecting samples to increased cycles of UV light, heat, condensation, and sprayed water to simulate accelerated outdoor conditions for testing. Short cycles of spray will imitate driving rain, while longer exposures of UV-B light will mimic the intensity of UV exposure that the site receives due to its altitude of 6,400 ft, alongside some heat exposure. While the artificial weathering operates in more intense, concentrated cycles than those seen in nature, the patterns of weathering observed on the samples and the effects on the coatings should be a good indicator of longer-term performance of the wood and the products. Further outdoor testing on site will be conducted subsequently in the summer of 2015 to confirm laboratory results in the field.

1.1 The Bar BC Dude Ranch

Figure 1. The Main Cabin with a view of the Teton Mountain Range. Photograph by the author.

In the preservation of historic sites and their architecture, preservationists must take the intentions of the past residents into account when designing treatments and maintenance plans. While this thesis explores treatments that can be applied to many similar cultural heritage sites in the area, its main focus is on the log structures of the Bar BC Dude Ranch. The Bar BC, located at 43° 41′ 42″ N, 110° 41′ 42″ W (43.695, -110.695) off of Teton Park Road, is the oldest extant dude ranch in the region, and the cultural resource staff of Grand Teton National Park and the Western Center for Historic Preservation have shown a great deal of interest in reviving the site.

A 1993 historic structures report conducted for the National Park Service along with previous theses concerning the structures found at the Bar BC have extensively explored the history of the site (Graham and Associates 1993; Doubledee 2014; Beckman 2013; Cantu 2012).

The Bar BC was the second dude ranch founded in Jackson Hole after a venture between Struthers Burt and Lewis Joy to form the JY Dude Ranch ultimately failed. Burt then went on to establish the Bar BC with Horace Carncross, the JY ranch's resident physician, in 1912 (Cantu 2012, 30). Much of the early history and anecdotes of life at the dude ranch originates from Struthers Burt's *Diary of a Dude Wrangler*, published first in the *Saturday Evening Post* and then in a book in 1924. Both this and his wife, Katherine's, stories and Hollywood involvement in Western films greatly contributed to the romanticized image of the west that made many Easterners make the long journey to the Rocky Mountains to live in rustic, simple conditions for months at a time. Bar BC hosted many notable public figures such as Mrs. Grover Cleveland, Wilson Eyre, Henry Van Dyke, George B. McClellen, Jr., David Adler, Alfred A. Knopf, Countess Eleanor (Cissy) Medill Patterson Gisycka, Ernest Hemingway, William Faulkner, John D. Rockefeller, Jr., and many more seeking a rustic cowboy experience (Cantu 2012, 39). The vernacular western log cabin was ideal for the location and purpose of the dude ranch: the structures were easy and cheap to build, materials could be sourced locally, and the rough, romantic aesthetic of the cabins was exactly what Easterners expected to encounter in their adventures as a Western dude or dudene.

In the United States, the log cabin began as a form utilized by Swedish and later German settlers largely in Pennsylvania (then "New Sweden") in the mid-17th and 18th centuries. The form was easy to construct, had a tradition of use in Northern Europe, and materials were readily available in the dense forests of North America. Log construction was later carried across the country by early pioneers in Westward expansion; the first wave of frontiersmen would build one-room, one-story log structures for a short one to two year habitation before moving on. Later waves of settlers modified these cabins with amenities such as windows and larger outbuildings for long-term occupation (Beckman 2013, 4-6). However, by the mid-19th century, balloon framing superseded log construction because of the widespread availability of sawn dimensional lumber and machine-made nails.

The Great Camp Movement that originated in the Adirondack Mountains of upstate New York in the 1870s revived the popularity of the log cabin; as the rustic revival style moved westward, it became increasingly aligned with the term “cowboy style.” These buildings became indicative of a new style of American architecture and were strictly utilitarian in execution and design; they were characterized by low-pitched roofs, log construction, concentrated use of local materials, quasi-professional or non-professional labor, rectangular shape, rectangular shape and compactness in scale, and little use of paint. The logs were rarely dressed and were often left to weather to a silver-brown in “ecologically unobtrusive” design, though this was more likely originally due to constraints on time and money rather than a conscious decision (Graham and Associates 1993, 11). This form of building was eagerly embraced by Burt and Carncross who had just two months to build the ranch after purchasing the land in 1912 before their first guests arrived for the summer. Although the two men started construction with the help of men from nearby Jackson who were somewhat familiar with log construction techniques, they eventually erected most of the ranch buildings with just the help of their ranch hands who were inexperienced in construction (Beckman 2013, 14). The first cabins were 12’ x 14’ because the logs were cut to specifications off-site; they were assembled using either notched or hog trough construction and chinked with course river sand and lime to keep the weather out.

Figure 2. Notched construction seen on the Main Cabin. Photograph by Christine Leggio for the Bar BC Condition Assessment and Report, 2011 by the Architectural Conservation Laboratory.

Figure 3. Hogtrough construction seen on a Dude Cabin. Photograph by the author.

The lodgepole pine logs used for the cabins as well as the river stones used for corner foundations and chimney stacks were harvested from the knob of trees about a half mile northwest of the site deemed Timbered Island, a lodgepole pine forest surrounded by sagebrush flats. Transportation of the materials to the site would have been fairly easy by land on wagons or water by floating down the Snake River (Graham and Associates 1993, 12).

Figure 4. Location of Timbered Island in Relation to the Bar BC Dude Ranch. Weather Access Map: Jackson Hole, http://www.mountainweather.com/index.php?page=TetonAreaMap.

In order to save time, logs were left undressed and the door and window frames were ordered from a catalogue and fit into the log structures while rough furniture was made on site (Cantu 2012, 35). These structures were by no means equipped for Wyoming winters, but the dude cabins were only in use during the mild summer months so this simple assembly was perfect for the ranch's needs. Nathaniel Burt, Struthers and Katherine's son, noted in a 1991 interview that these structures were treated with oil, making them dark both inside and out (Graham and Associates 1993, 41).[4]

The ranch in its heyday hosted forty-five structures spread over six hundred acres of land, though there was a concentration of buildings around the central main cabin and prominent corral at the entrance. Building types included the main cabin, dude cabins, ranch store, post office, dance cabin, saddle sheds, barn, blacksmith and carpentry shops, icehouses, bunkhouses, boy's camp, outhouses, and other service buildings (Graham and Associates 1993, 21). Life on the ranch was dictated by the design of the site and its architecture. The private guest cabins were relatively small and mostly used for rest and respite whereas the main cabin served as the main socializing point for the entire ranch; there were living rooms, a card room, and a writing room for indoor recreation, and both guests and employees ate in the dining rooms there. Other public outbuildings served as additional gathering points and bases for outdoor recreation such as horseback riding, fishing, or hunting.

The Bar BC was incredibly popular throughout the 1920s, but began to decline slowly after the Great Depression and later with the advent of the motor age. Burt and Katherine pulled out of the management in 1930 shortly after Carncross' death because of a fallout with their third partner, Irving Corse; Corse, however, continued to run the ranch as a dude retreat into the 1940s. The appeal of the dude ranch and vacationing in one location faded as America became more focused on automobile transportation. The ease of travel caused tourists to stay in one location for only a few days before moving on rather than remaining for extended periods of time. Thus, the Bar BC adapted to the times; after Corse's death in 1953, his wife retained life estate and rented the cabins out to sightseers during the summertime. She

[4] In the interview Burt does not distinguish what kind of oil was used to treat the cabins. The oil used for the waterproofing and protection of the logs was likely linseed oil or a similar natural drying oil.

surrendered her life tenancy in 1986 and after a brief legal dispute both the land and the buildings on them were transferred to the National Park Service (Cantu 2012, 32).

1.2 Site and Climate Conditions of Grand Teton National Park and the Bar BC Dude Ranch

1.2.1 Site

Grand Teton National Park, established on February 26, 1929 and later expanded into the valley called Jackson Hole in 1950, encompasses an area of approximately 310,000 acres (485 square miles) in northwest Wyoming. It is only ten miles south of Yellowstone National Park, the first national park established in the United States in 1872, and the combined area protected by the National Park Service in both parks constitutes over 18 million acres (Cantu 2012, 40). A plethora of historic log structures survive in both parks ranging in size and complexity from small guest cabins on dude ranches to the Old Faithful Inn, a pinnacle monument in western log construction.

Grand Teton National Park includes the major peaks in the 40-mile-long Teton mountain range and part of the Jackson Hole valley. The Tetons rise abruptly from the rather level surroundings, ascending over 7,000 feet with no foothills (Doubledee 2014, 18). Grand Teton, the tallest mountain in the region after which the park was named, stands at 13,700 ft while the valley below is at an average elevation of 6,800 ft. The high elevation of the area results in greater ultraviolet exposure because there is less atmosphere containing radiation-absorbing chemicals such as ozone to suppress the UV radiation before sunlight reaches the ground. The local ecosystem contains alpine and sub-alpine mountain systems, six glacial lakes at the base of the range as well as over one hundred alpine and backcountry lakes, the Snake River, seven species of coniferous trees, over nine hundred species of flowering plants, and great diversity of wildlife (United States. National Park Service, "Park Statistics"). It is this resource-rich and visually stunning environment that first brought humans to the area, ranging from Paleo-Indians to French fur trappers, ranchers and farmers, and later to recreational tourists such as dudes.

Figure 5. Some of the prominent features of Grand Teton National Park. United States Geological Survey (USGS).

The Bar BC Dude Ranch is located on the western bank of the Snake River, which divides the valley in half, in the bottomlands between the river and an escarpment that leads to the tablelands of Jackson Hole and the Teton range due west (Doubledee 2014, 22). Access to the site is a bit difficult, especially for tourists that are not certain of the location. The ranch is located about a mile and a half down a rough, rocky road through the plains off of the main thoroughfare of the Park. This journey would have been even more arduous in the early 20th century because it would have been preceded by a six-day train ride from the east coast to Idaho and two-day wagon ride from the southwest before making the final bumpy trek to the ranch (Graham and Associates 1993, 16, 24). Due to its lower elevation in the river valley, the site is not visible from the road until guests arrive at the gates. This remote quality has somewhat limited visitation to the site in recent years except by more adventurous sightseers or those that remember staying in the area when the Ranch was still operative. However, cultural resources staff are giving the site more exposure in an attempt to increase visitation.

1.2.2 Climate

The park is located in climate zone 7B, a semi-arid mountain climate with mild summers and long, very cold winters; spring and autumn seasons are very brief. According to National Weather Service data compiled from 1958 to 2010 in Moose, Wyoming, located just a few miles south of the Bar BC, average temperatures range from 0.9 ˚F in January to 80.5 ˚F in July, with an extreme low of -63 ˚F in the winter and an extreme high of 97 ˚F in the summer. Daily ranges in these extreme seasons on average span from 1 ˚F to 26 ˚F in the winter and 41 ˚F to 80 ˚F in the summer. The average precipitation for the area is 21.32 inches and the average snowfall is 172.6 inches.

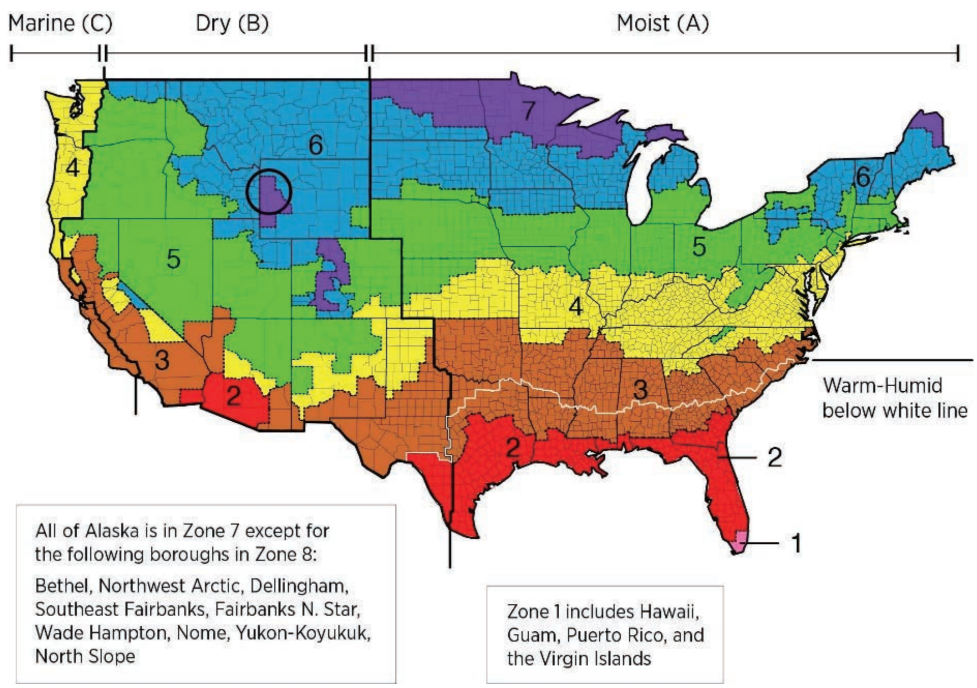


Figure 6. IECC Climate Zone Map with Grand Teton National Park and surrounding area encircled (U.S. Department of Energy, 2012).

Month	Average Maximum Temperature	Average Minimum Temperature	Average Precipitation (inches)	Average Snowfall (inches)	Average Snow Depth (inches)
January	25.9	0.9	2.59	43.3	28
February	31.1	3.3	1.89	28.8	33
March	39.3	12.0	1.57	20.1	31
April	49.3	22.2	1.49	9.2	12
May	61.0	30.8	1.91	2.4	0
June	70.7	37.3	1.76	0.1	0
July	80.5	41.5	1.16	0	0
August	79.0	39.6	1.35	0	0
September	69.1	32.2	1.44	0.4	0
October	55.7	23.1	1.44	4.8	0
November	38.3	13.7	2.16	23.4	4
December	26.5	1.9	2.55	40.0	16
Annually	52.2	21.6	21.32	172.6	10

Table 1. Chart of averaged weather data collected from Moose, Wyoming from December 14, 1958 to December 31, 2010 (National Park Service, 2011).

This data suggests that the climate is very dry with a low relative humidity throughout most of the year and most precipitation occurs during winter months. Heavy snow loads from November to April can create problems both with overloading the unstable historic structures as well as establishing constant water exposure through daily cycles of freezing and thawing on the lower portions of these structures for months at a time.[5] Summer months often include afternoon thunderstorms that move swiftly up the valley from the southeast, exposing structures to heavy rain and sometimes hail for short periods of time. The low-humidity environment in addition to the intense sunlight results in fairly quick drying of the surface material, however, so the wood is additionally stressed by shorter cycles of absorption and desorption which frequently results in checking. These checks occur naturally in wood when stresses occur along the grains created by the fibers of cellulose and are usually not a source for alarm in themselves; however, upward

[5] The significant effect of heavy snow loads on the structural support of the cabins is extensively addressed in Christine Beckman's thesis (Beckman 2013).

facing checks warrant concern for their ability to gather and hold dirt, debris, and water, creating environments conducive to decay. According to a condition assessment survey of the site conducted by the University of Pennsylvania's Architectural Conservation Laboratory in 2011, cabins oriented with their larger elevations facing north and south displayed much worse conditions due to prevailing winds and sun exposure, especially on the southern elevation (Cantu 2012, 45). This demonstrates that the degradation of lignin by UV radiation and the subsequent removal of surface cellulose and other wood material by abrasives carried in the wind or water is one of the major degradation mechanisms of the site. Additionally, some of the structures surveyed show evidence of the deeper penetration of ultraviolet radiation, and thus greater degradation, into the end grain than across the grain.[6]

1.3 Traditionally Applied Wood Treatments

Cultures that have traditionally used wood as a building material have developed various techniques for its protection from rot and decay. The evolution and success of these treatments depended on the environmental conditions of the area as well as the available resources, but most treatments for wood involve regular maintenance and reapplication in order to ultimately be successful. Wood will last longer if it is regularly treated with finishes that add water repellency and prevent cracking and weathering while inhibiting fungal growth (Morrell et al. 2001, 27).

Due to a preponderance of pine trees in the area, Scandinavian cultures traditionally protected buildings using pine tar resin.[7] However, medieval log buildings were neither tarred

[6] Studies have shown that ultraviolet light can more readily penetrate the open pores of the transverse sections of wood exposed in end grain than the tangential section exposed along the length of the tree.
[7] These resins are known to contain tricylic diterpenoid resin acids, tricyclic diterpene hydrocarbons, alkylphenanthrenes and fatty acids, but the composition depends on the production process. Tradition kiln produced pine tars from Norway analyzed using gas chromatography-mass spectrometry (GC-MS)

nor given other forms of surface treatment because they were thought to possess enough of a protective surface layer and only a relatively small amount of pine tar could be produced with each batch (Egenberg 2003, 4). Thus, prominent buildings of wooden shingle construction, such as the Viking stave churches of Sweden and Norway, were usually the recipients of the pine tar treatment. The product was collected using carefully built kilns which would distill down the resins in the heartwood of old pine trees over a period of a few days as operators skillfully manipulated air flow, heat, and material. This process has been carried out in Norway since the early medieval period and small batches are still made every few years (Egenberg 2003, 2). The finest pine tar, a very light and more viscous product, came out of the kiln in the first part of the distillation process and was used on the prominent buildings such as stave churches. Any product that came out later was darker and of a lesser quality, and, if enough was produced to protect civic and religious buildings, could be used to protect wooden houses (Egenberg 2003, 3).

showed a large variety of chemical components, though the main components were found to be dehydro abietic acid and abietic acid (Egenberg 2000, 148-154).

Figure 7. Heddal Stave Church in Telemark, Norway. http://www.traveltourismblog.com/norway-landmarks.php.

Mandates in medieval law required that peasants produced this tar every three years and coat the church. This regular maintenance and effective coating have protected the stave churches for over eight hundred years with minimal replacement of wood material. Contemporary recommendations for the preservation of these churches are only slightly modified, calling for re-tarring on sun-exposed surfaces every three years and shaded areas every six (Egenberg 2003, 2). The tar coating is very distinctive and tends to form a shiny appearance, so it is not necessarily an appropriate choice for use on Rocky Mountain cabins that were traditionally uncoated or treated with just linseed oil. However, some more recent products out of Sweden incorporate the pine tar resin into a thinner coating that has less impact on the visual appearance of the wood and could be worthy of future testing.[8]

Linseed oil was commonly used, and is still used, for its hydrophobic properties and deep penetration into wood surfaces for protection from water and rot. Even a thin layer can reduce wood movement and cracking by preventing rapid surface absorption and avoiding steep surface moisture gradients. Surfaces must be cleaned before application, however, or dirt and debris can become engrained in the finish and turn the wood black, and once linseed oil has cured then it is very hard to remove (McCaig and Ridout 2012, 401-3). It is a drying oil, so it dries through the chemical process of oxidation and can polymerize into a solid form. Upon exposure to oxygen, the large amount of α-linolenic acid in the oil reacts to form polymer chains that crosslink and results in the increased rigidity of the oil. Linseed oil is the product of cold-pressing seeds from the flax flower. The raw oil never fully dries and is much fattier, so professionals utilize boiled linseed oil, a product resulting from the refinement of raw linseed oil through the addition of oxygen; lower quality linseed oil products often include chemical dryers as well. This "cooking" process reduces the amount of proteins and impurities in the oil, improving drying time and shine and reducing the fat content of the oil. In more modern finishes, linseed oil is often modified to form alkyd resins to make them less prone to mildew as well (Knaebe 2002, 1-2).Unfortunately, because of its fatty acids, linseed oil is especially attractive to insects and thus, if not successfully boiled, can encourage infestations even as it acts as a hydrophobic barrier to water. Therefore oil treatments have often been mixed with anti-fungal agents or pesticides. The first patented wood preservative process was a method devised by a Mr. Emerson in 1736 for the saturation of timber with boiled oil containing 'poisonous substances' (Ridout 2000,

[8] Auson Pine Tar, http://www.solventfreepaint.com/pine-tar.htm.

100). By itself, however, linseed oil is a food-grade, nontoxic, and edible oil and thus is an environmentally-friendly treatment.

Linseed oil has a history that dates back to ancient Egypt. Oils and fats were often used by ancient peoples for food, illumination, and medicine as well as lubrication and wood treatments. The Egyptians were especially skilled at combining oils and resins for objects such as wooden mummy cases. Additionally, the Greeks and Romans used drying oils for an ink medium. Evidence of written paint and enamel formulations date back to the 6^{th} century, and a passage from Theophilus Presbyter describes varnishes and paints containing linseed oil and resins in the 12^{th} c (Eastman 1968, 123). In the United States, where it has been produced since 1793, linseed oil was valued for its protective power. Until WWI, it was the principal vehicle available in the US for protective coatings, a drying oil vehicle in paints, varnishes, enamels, oilcloth, patent leather, and many other specialty items. Fluctuations in price and unreliable harvests drove the government to invest in research for alternatives; along with the post-war boom in the chemistry industry, linseed oil was quickly phased out in favor of colloidal resins, acrylics, and other new products with superior coating properties such as a faster drying time (Eastman 1968, 129-30). However, linseed oil is still widely available and some companies have continued to produce traditionally formulated linseed oil paints for the market.

Historically, natural waxes such as beeswax have been used more often in waterproofing objects and building materials. However, as technology has progressed, waxes with slightly different properties have been developed. Paraffin wax is a petroleum byproduct and is a fairly inert mixture of hydrocarbons that form a slightly brittle wax with a melting point around 99 ˚F. This higher melting point and the brittle quality make it a much better choice for exterior waterproofing because, except under very high heat, the wax will not melt and hold any dirt or soiling particulates delivered by wind thus changing the appearance of the building. The wax alone does not penetrate deeply into the wood surface, so waxes have been mixed with mineral spirits, turpentine, mineral oil, and many other diluents or vehicles in order to achieve greater penetration. Additionally, most recipes call for the mixture to be lightly heated in order for the treatment to permeate the wood. Subsequent applications can also be applied once the first coat dries (McCaig and Ridout 2012, 403). One of the main benefits of the wax and mineral spirits treatment is that, like linseed oil, it is relatively nontoxic to the environment.

1.4 Transition into Formulated Treatments

The traditional treatments detailed above provide virtually no ultraviolet protection for wood surfaces because they are largely transparent, though they tend to yellow in appearance under UV exposure. The most effective treatments for light damage on wood are entirely opaque paints or stains with high pigment particle counts which literally block the surface of the wood from sun damage as a sacrificial element. However, paints and opaque stains effectively change the appearance and character of wood surfaces and are not a viable option for traditionally uncoated sites whose character is expressed by the visibility of the natural materials. Semi-transparent stains, basically water repellent preservatives with light pigmentation, could potentially be used, but the color of the pigmentation could have a significant effect on the site. The paint industry has invested an immense amount of time and resources into the technology into this problem of protective yet transparent finishes. This fascination can be partially attributed to the Arts & Crafts movement at the turn of the 20th century because of its emphasis on the beauty and honesty of natural materials. This interest in the aesthetics of natural wood features on houses continues today across the US, especially in the field of wooden decks. Many of the stains produced now are marketed to homeowners as a way to showcase their beautiful deck while still protecting it. Thus, the wood protection industry, in response to the desired natural appearance and the rapid advances in the chemical world, has experimented with a variety of protective coatings with varying degrees of success.

The government also became involved in this venture through the work of the Forest Products Laboratory (FPL) in Madison, Wisconsin, a national research laboratory of the Forest Service under the US Department of Agriculture. The stated goal of the agency is to promote healthy forests and forest-based economies through the efficient, sustainable use of the nation's wood resources. Experts in the field of wood have worked on vital research endeavors into the study of the material as well as its protection since the foundation of the laboratory in 1910. Much of the early literature on the degradation process of wood and possible treatments for its protection derives from this agency's publications. The Madison Formula, an easy and highly effective water repellent preservative developed around 1950 that was ultimately discontinued due to its toxicity, originated through the lab's research as well, deemed the FPL treatment. The treatment combined a linseed oil base and mineral spirits for penetration with the fungicide pentachlorophenol, paraffin wax for waterproofing, pigments for stain colors, and zinc stearate for pigment suspension (Black et al. 1979, 2-3). However, pentachlorophenol, "penta" for short, was outlawed for home use in 1985 by the Environmental Protection Agency (EPA) and is now only available for registered companies as an insecticide.[9] No other insecticides on the market that are readily available to the homeowner can compare to the preservative power of penta and other strong pesticides, though the FPL has made a few other suggestions based on the formula. The EPA has also limited the formulations of many solvent-based paints, stains, water repellent preservatives, etc. on the market because of the Clean Air Act, originally

[9] The main danger with using pentachlorophenol lies in bio-accumulation the soil and atmosphere and the subsequent increase in toxicity as it accumulates. As the wood deteriorates on site or in landfills of discarded material, the chemical is released into the soil and then the ground water, having a profound effect on the surrounding ecosystem.

enacted in 1970 with later provisions. This has pushed the industry to look more seriously into lower VOC solvent- and water-based products in the past few decades.

The experimental research that forms the basis of this thesis strives to determine the effectiveness of some of the top-rated treatments in this new wave of more ecological and UV resistant products as compared to some of the widely used historical treatments although several of the latter have been included for comparison.

Chapter 2: Literature Review

This review examines the technical literature on the usage of hydrophobic and ultraviolet protective treatments on the exterior of wooden structures, with a particular emphasis placed on the recent use of UV reflectors and inorganic nano-pigments, and their durability as observed in accelerated weathering tests that can be used to measure the efficacy of these treatments. Although biocidal wood preservatives are very important in the maintenance of wooden structures, they are generally not considered in this review unless included in formulations with the aforementioned protective treatments, such as in water-repellent preservatives or in coatings rich with zinc oxide particles. UV and water repellent treatments have been prioritized to accommodate the climate of the Bar BC Dude Ranch in the Rocky Mountain western region, the primary testing site for this program. For the most part, the cabins have not been significantly affected by either fungus or insect attack. This site is regulated by the National Park Service and treatments must be environmentally acceptable, commercially available, long-lasting, and able to be easily applied on the park’s historic log cabins in situ.

In historic preservation, clear finishes for exterior wood elements are often part of the aesthetic ideal for properties that have traditionally possessed uncoated wood surfaces. However, when these surfaces are exposed to weathering, especially the degradative effects of ultraviolet (UV) light, it is often impossible to maintain adequate protection of the original material. If the coating does not possess certain additives that can block the damaging effects of UV irradiation on the microstructure of the wood, particularly on the lignin found in and around cell walls, then the wood substrate will change color, degrade and lose its cohesive strength with weathering (Borgin, 1968; Singh and Dawson, 2003; Macleod et al., 1995; Ridout, 2000; Kishino and Nakano, 2004). Often UV light can degrade the coating as well, causing it to fail even before the substrate (Miniutti, 1967b). Advances in technology have provided many new methods for enhancing the durability of these coatings and their UV protective power among other properties to greater or lesser extent. Some suggested application methods such as heat treatments, submersion in treatment, or grafting of nanoparticles or UV absorbers to the surface of the wood substrate appear to function very well, but are not viable for site application and are thus largely not addressed in this thesis (Williams, 1983; Kiguchi et al., 2001; Sun et al., 2012). These clear coatings have traditionally been solvent-based, but due to EPA Regulations restricting Volatile Organic Compounds (VOC's) largely beginning with the Clean Air Act amendments in 1990 and with further state restrictions in states such as California, waterborne coatings have become more commonplace over the past twenty years. Waterborne coatings are often just solvent-based finishes such as acrylic or polyurethane that are dispersed in water (Flexner, 1996). These coatings sometimes do not perform as well as solvent-borne, but with future restrictions due to increasing environmental regulations being imminent, waterborne treatments are considered in this thesis (de Meijer, 2001).

2.1 Wood Degradation by Ultraviolet Radiation

The forefront leader in wood research in the United States since its founding in 1910 is the Forest Products Laboratory (FPL), a research facility for the US Department of Agriculture out of Madison, Wisconsin. The mission of the FPL is to identify and conduct innovative wood and fiber utilization research that contributes to conservation and productivity of the forest resource in order to sustain forests, the economy, and quality of life; a great deal of the articles available to the public, both scientific and informal, over the past century have derived from the scientists and wood technologists involved in this organization. Most of the early research conducted by the lab established the importance of the wood substrate in the performance of finishes; thus, early interest in the degradation mechanism of ultraviolet light began in the FPL (Gorman, 1989). The examination of the degradation methods of UV light revealed that the decay of lignin, largely found in the middle lamella region between the cell walls, is the primary deterioration mechanism due to ultraviolet light exposure, though all components of wood are somehow affected by the light energy (Miniutti, 1967a; Miniutti, 1970; Chang et al., 1982; Wypych, 2013). As the lignin decays, only the cellulose of the cell walls remains, as it is essentially unaffected by the ultraviolet light (Kishino and Nakano, 2003); the presence of this structural material with little material holding it together leads to the instability of the de-lignified surface and its eventual loss by abrasion. Additionally, the hydroxyl groups from the cellulose lead to the increase of the wettability of the wood (Wypych, 2013). Wood fabric combined with water proves to be much more affected by UV degradation than wood exposed to light alone, so the hydrophilic qualities of the cellulose surface degrade the wood substrate even more quickly (Anderson et al., 1991a; Anderson et al., 1991b). Different species of wood weather differently and can still be distinguished by their IR spectra during the early degradation process; however, after 2400 hours of artificial weathering, the features become the same due to the high quantity of mostly cellulose found on the surface (Anderson et al., 1991b).

Various experiments have led to observations on both coated and uncoated wood before and after natural or artificial weathering. These observations have been carried out both by eye and by instruments with different types of physical and chemical analyses such as Scanning Electron Microscopes (SEM) (Miniutti, 1970; Chang et al., 1982; Dhoke et al., 2009; Sun et al., 2012), Fourier Transform Infrared Spectroscopy (FTIR) (Macleod et al., 1995; Schmalzl and Evans, 2003; Norman et al., 2004; Dhoke et al., 2009; Sun et al., 2012), Reflected light and fluorescent microscopy (Miniutti, 1967b), X-ray Diffraction (XRD) (Sun et al., 2012), and Atomic Force Microscopy (AFM) (Dhoke et al., 2009). These analytical methods were used in order to understand both the physical and the chemical process by which the wood breaks down. Initial observations record the enlargement of micropores in the tracheid walls, tracheid embrittlement, and formation of microchecks in and around the tracheid walls; these were especially prevalent in the earlywood as opposed to latewood. These cracks are the source of the instability of the wood substrate that can lead to fabric loss as well as coating cracking or flaking (Miniutti, 1967b). The chemical mechanism has been investigated further over the past fifty years, and many books and articles addressing wood and its weathering have elaborated on the subject of physical and chemical degradation to a greater or lesser extent; however, the full interaction of all of the factors involved in the variety of mechanisms leading to degradation has not been entirely revealed (Evans, 2008; Williams, 2012; Hon, 2000). Generally, as the readily-light absorbent lignin takes in the energy of the ultraviolet light, various bonds in its structure break, releasing phenoxy free radicals (Wypych, 2013). These radicals react with atmospheric oxygen and other radicals to form peroxy radicals that can attack polymer chains such as the hemicellulose and cellulose molecules in the wood fabric, causing photo-oxidation.

Studies show that ultraviolet light cannot penetrate the surface deeply, only about 75 microns while visible light penetrates no more than 200 microns (Browne and Simonson, 1957) though century old wood can be degraded more deeply, 6-7 mm, with faster changes at the beginning of the degradation, resulting in losses down to 3 mm in one year of exposure (Wypych, 2013). Additionally, the weathering process by UV light is slow, the exact rate of erosion varying with species and density of the wood along with the weathering conditions; typical softwoods lose about ¼” every century (Sell and Feist, 1986; Browne 1960). However, these small increments in loss should not be taken for granted; wood surface degradation should be avoided to prevent the loss of any historic fabric or finishes the surface may have had. Additionally, while the full-round logs of the guest cabins at Bar BC may have large material loss tolerances before they are considered a serious problem, many wooden elements such as shingles, veneers, or detail elements are much thinner and thus more affected by surface delignification and loss. Surface and subsurface treatments have the potential to alleviate material loss by deflecting the penetration of ultraviolet light before it can degrade the wood.

2.2 Treatments for Weathered Wood

Weathered wood surfaces do not hold film coatings very well; even though they readily take in primers and penetrating stains, coatings tend to not adhere. Studies have been conducted to try to remedy this problem in light of the fact that large wood surfaces (especially historic ones) cannot be sanded down to sound substrate before treatment (Wypych, 2013). Natural weathering testing with more penetrative coatings on extremely weathered red cedar showed that coatings with oil-based components, such as oil-modified-latex finishes, stabilized the weathered material (Williams et al., 1999). These stains are not film-forming and therefore will not peel or flake off of the surface. Water repellents and water-repellent preservatives belong to the category of penetrating finishes. These finishes afford protection and dimensional stability during the early stages of weathering due to their hydrophobic properties (and biocidal properties in the case of water-repellent preservatives), but as the weathering process continues the finish tends to become less effective (Borgin, 1968; Bulian and Graystone, 2009). Additionally, replications of these treatments tend to adhere to the firm base of non-weathered wood more readily than the damaged base of weathered substrate (Williams, 2012). However, the treatments, water-repellent preservatives in particular, prove to be effective pre-treatments to coatings, and thus would be highly effective as a further protection method combined with a transparent coating (Feist, 1990; Williams and Feist, 1999).

2.3 Wood Surface Protection through Reflectors and Pigments

Although reflectors and pigments comprise only one category of the possible treatments for ultraviolet protection for exterior wood, they are an especially appropriate treatment due to their historic usage and relative ease of application for field use in most forms. Additionally, they have been adopted into the commercial paint industry (and touted by many companies rather than concealed in mystery formulations). These inorganic particles are deposited on or slightly within the surface of the wood substrate, depending on application method, and their main function lies in blockage or scattering of light rays away from the wood fabric so that the lignin in the wood fabric does not degrade. Opaque paints and stains have been used as a method of protection and decoration of structures and objects for thousands of years, if not longer. The Forest Products Laboratory has been recommending their use since the lab's inception, and has worked to understand the influences that affect the service life of wood finishes and the most effective ways in which to protect wood (Gorman and Feist, 1989). However, in the protection of historic natural wood surfaces, the conservator must consider that the usage of opaque pigments results in the color change of the wood substrate at least, if not in the total concealment of the wood grain and color. Thus, traditionally this change could have been evaluated as an aesthetic sacrifice in order to better save the fabric of the wood; however, with the advent of new technologies in pigment manufacture, transparent coatings for 'natural' wood may be accessible.

Nano-sized reflectors and pigments have been shown to offer protection from UV degradation in a variety of studies. While they tend to perform better in conjunction with other UV retarding processes they do offer a good deal of protection for the wood surface by themselves. The British physicist Lord Rayleigh was the first to note in 1871 that small particles scatter light in a manner inversely proportional to the fourth power of the wavelength of the light (Blackburn et al., 1991). Thus, the shorter the wavelength, the greater the scattering by smaller particles. This is especially relevant to ultraviolet wavelengths that range from 100-400 nm, with lignin degradation occurring especially around 300 nm. With the technological advances, it has become possible to grind traditionally used additives and pigments such as iron oxides, zinc oxide, and titanium dioxides to a nanosize that makes them more widely dispersed throughout the treatment and largely transparent, allowing the surface of the wood to show through the coating. Nanometals are more stable than organic absorbers and can be used in both oil- and solvent-borne coatings, an advantage in a more environmentally conscious world. Additionally, these nanopigments are fairly cheap to produce and are increasingly being utilized in commercially available clear wood coatings and stains.

The low viscosity of the mixtures combined with the high dispersion ability also allows for even particle distribution across the surface; the large concentration afforded by the smaller sizes of the particles also allows for the release of a larger number of metal ions that can inhibit microbial growth on both the coating and the wood substrate (Clausen, 2012). The nanometals perform much better pre-dispersed in a coating rather than in powder form due to higher vapor permeability and more even distribution (Vlad-Cristea et al., 2012). Studies have shown that the nano-sized particles are also more photoactive than pigment-sized particles, likely due to increased surface area, enhancing their photostability (Allen et al., 2004). Additionally, being inorganic, they are inherently stable as well and can be used in coatings where water is the solvent, a quality that is important in today's transition into low VOC coatings. Organic particles, on the other hand, have a tendency to migrate or decompose during weathering (Allen et al., 2002a). These light scattering nanoparticles are often combined with other UV resistant additives such as UV absorbers or radical scavengers such as hindered amine light stabilizers (HALS) in order to enhance the durability of clear coatings. The results of these combinations are usually more favorable than any one method alone (Allen et al., 2002a; Allen et al., 2002b; Allen et al., 2004). However, these other additives will not be addressed at depth in this research.

2.4 Commonly used Pigments for Protection from Ultraviolet Radiation

2.4.1 Titanium Dioxide (TiO_2)

Titanium dioxide is a white pigment that has been traditionally used in most paints since the early 20th century due to its brightness and high refractive index causing greater opacity. The pigment also possesses strong light absorbing capabilities and is resistant to discoloration through UV degradation (Wypych, 2013). Titanium dioxide is not only utilized in the coatings industry, but also by plastics, cosmetics, sunscreens, and a variety of other industries utilizing pigments. Some have found it ineffective in blocking UV, but for the most part, experimentation has shown relative success of TiO_2 (Vignolo, 1995; Cristea et al., 2011). The rutile form of titanium dioxide has typically been proven to be more appropriate for usage in UV absorption than the anatase form; it absorbs more strongly at higher wavelengths and usually works synergistically with organic UV absorbers and HALS, while the anatase form actually acts as a photocatalyst, does not opacify as strongly, and works against other UV systems (Allen et al., 2002b; Allen et al., 2004; Sun et al., 2012). However, positive effects of photostabilization can be seen in both rutile and anatase forms of titanium dioxide, making it an effective and cost-effective translucent filler for the coatings industry (Allen et al., 2002a).

2.4.2 Zinc Oxide (ZnO)

Nanozinc particles have the benefit of being both less opaque when reduced into smaller particles as well as imparting hydrophobic and biocidal properties to the wood that greatly reduce fungal and insect attack (Clausen et al., 2009; Clausen et al., 2010; Clausen, 2012). They have been shown to reduce the degradative effects of accelerated xenon weathering including yellowing and degradation of surface (Salla et al., 2012). Similar to titanium dioxides, zinc oxides have a variety of applications in the coating industry and can be seen to improve the UV resistance of a variety of materials including metals, textiles, and plastics (Dhoke, 2009). The particles perform well in waterborne coatings as well, with some studies showing that higher concentrations provide greater UV protection (Dhoke, 2009) while others showed that the protective abilities of the nanometals begin to decrease at higher concentrations and volumes around 2 g/m^2 are ideal (>99% UV blockage) (Blanchard and Blanchet, 2011; Lowry et al., 2008). Studies have found zinc oxide to be a more effective UV protector than titanium dioxide; the pigment is both less white at all concentrations and more effective at blocking light (Pinnell et al., 2000). Zinc oxides tend to be more efficient at medium durations of light exposure; with the size, concentration, and form of the particles affecting their performance. Beyond 20 nm, smaller particle sizes were not shown to improve protection (Blanchard and Blanchet, 2011). CeO_2 Cesium dioxide particles performed well alongside micronized zinc oxide in tests, largely blocking color change in the wood substrate (George et al., 2005; Blanchard and Blanchet, 2011).

2.4.3 Iron Oxides

Transparent synthetic iron oxides can also be utilized for UV protection. These particles are usually smaller and allow transmission of visible light while shielding UV light; they have also demonstrated to be more stable and protective over longer periods than organic UV absorbers (Sharrock, 1990). They have also been combined with titanium dioxides to great effect (Blackburn et al., 1991). However, the particles tend to be colored; the pigmentation of the various oxidation states of the iron range from yellow to red. While inclusion of these particles may be an appropriate treatment for a wood substrate that is naturally warm-colored, this treatment is not necessarily appropriate for all structures. However, they are the source of the UV protection that most commercial product advertise today.

2.5 Commercial Formulae

Commercial products on the market today often don't list specific components in order to protect their trade formulae. Encyclopedic sources on the material qualities of various types of wood treatments go in depth into what components can be utilized for certain weathering-protective effects, but make no affiliation with particular commercial sources and products (Bulian and Graystone, 2009). However, if a component is considered potentially hazardous, it must be listed on a material safety data sheet (MSDS). Many clear or semi-transparent products that advertise UV protection contain light reflecting pigments, shown by their MSDS sheets, usually in concentrations of 5-10%. Titanium dioxide is often included, though its toxicity appears to be low due to its common use in many products that require light stabilization. The lack of information can lead to some confusion about what is producing certain results when pigments are added (Cristea et al., 2011); however, no additional nanopigments will be added to the commercial coatings or penetrating oils in this experiment, reducing possible crossed results.

2.6 Accelerated and Natural Weathering

These coatings were tested using the QUV Weatherometer, an accelerated weathering device that exposes samples to small, intense cycles of ultraviolet light, temperature stresses, and water spray as well as vapor. These machines can be used to test the degradation and weathering processes of a variety of materials, not just wood samples. Sample sizes are limited and testing brackets allow for samples to have set, restricted sizes. Cycles can be adjusted to suit the material, the goals of the experiment, and the environment of the test site, among many other variables (Wypych, 2013; Hoeflaak and Gard, 2001). The results of these tests are often more intense than can be seen in the field due to the aforementioned short, intense cycles, so often researchers have supported results with simultaneous or subsequent natural weathering testing as well.

Natural weathering testing is achieved when samples are places outdoors in varying configurations to determine different aspects of the weathering process on samples of uncoated or coated wood. North and south vertical configurations can give insight into fungal growth or ultraviolet irradiation on buildings; a 45˚ angle on a southern exposure maximizes radiation to the sample (Wypych, 2013). Much like with accelerated testing in the Weatherometer, in order to detect differences in coating performance, samples must have the least amount of variability between their substrates as is possible in wood. Backsides and endgrains of panels are often coated to prevent excess moisture that could lead to unrealistic cracking or warping. Outdoor testing has a variety of constraints that have to be addressed when selecting environment-appropriate laboratory testing: long duration of testing, climactic differences between locations, and repeatability and reproducibility of results (Graystone and Abrahams, 1996). Often, laboratory testing cycles and conditions have to be adapted in order to better meet the climate of the target area or the location of natural weathering to obtain similar results (Hoeflaak and Gard, 2001).

Chapter 3: Methodology

3.1 Sample Procurement

Due to its preponderance in the ecosystem of the Rocky Mountains as well as its tall, straight profile with little branches, lodgepole pine has been used as a building material for hundreds of years. *Pinus contorta latifolia* thrives in dry to somewhat moist open forests in moderate to fairly high elevations. All of the trees harvested from Timbered Island and the surrounding area for use in erecting homesteads and ranches like the Bar BC were lodgepole pine. Logs used currently by the Park Service in repairs and replacements for historic structures are still lodgepole pine, though the trees must be sourced from outside of the park. The replacement logs come from a few different sources usually over the mountains in Idaho. In order to best represent the wood that was historically used and is still being used today for repairs, samples for the experiment were obtained from a recurrent supplier, Willmore Lumber Co. Willmore, a company specializing in top quality wood for many spec projects, is located in St. Anthony, Idaho, less than one hundred miles away from Grand Teton National Park on the other side of the Rocky Mountains. I corresponded with Alan Willmore, one of the four owners of the company, to create a custom order of material that would be suitable to the project. The material used in this experiment came from logs sourced from an old growth pine forest.[1]

Samples had to be a certain size to fit inside the Weatherometer and full round logs or parts of logs could not fit into the machine. This along with cross-country shipping costs resulted in the decision to order smaller sections of cut wood to be further trimmed to size in the shop at the University of Pennsylvania. In an effort to imitate the outer sapwood that would be most affected by the exterior weathering, Willmore sent material that was cut off of logs while

[1] The trees were removed from a select area of the forest for the installation of a power line.

making dimensional lumber using a technique called plain or cant sawing; the rounded edge is cut off to produce a cant that is further cut to produce boards (as seen in Figure 8). This edge material consists of the outer 1-2 inches of the lodgepole pine logs that are roughly the same size as those used in the cabins at the Bar BC, about 10-12 inches in diameter. The cut sections were comprised of the bark and outer layers of sapwood. The final shipment of wood pieces consisted of forty slabs of dimensions approximately 12 x 4 x 1 ½ inches.

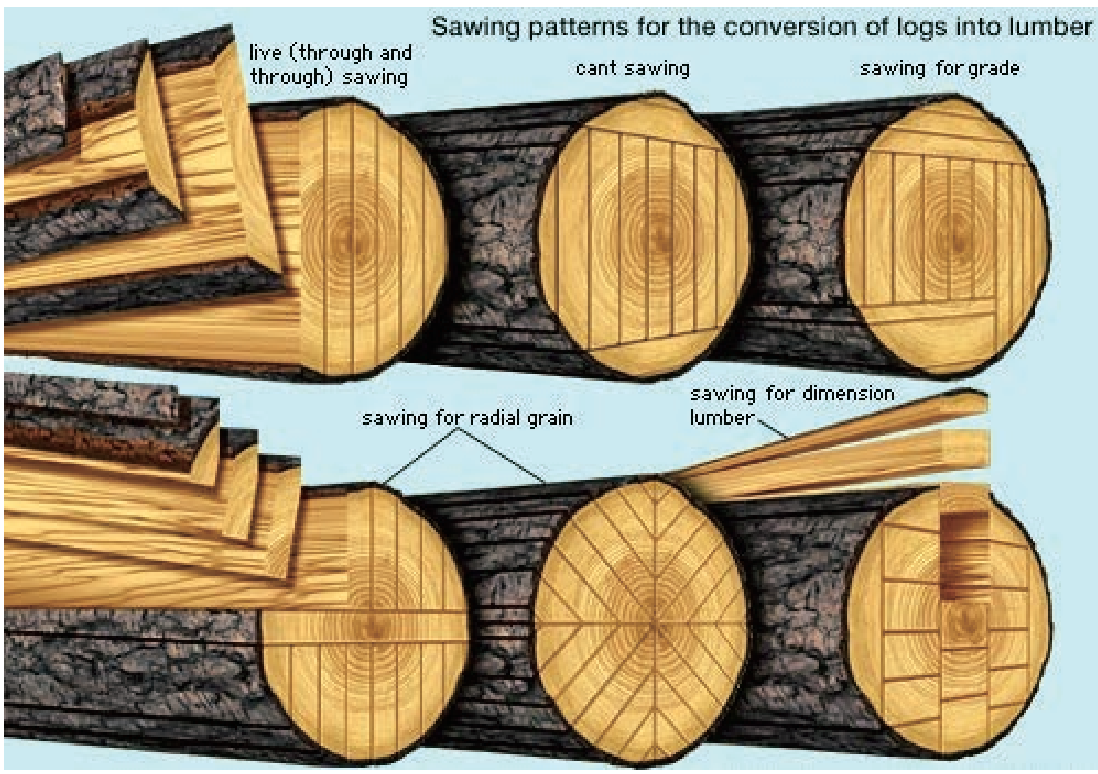


Figure 8. A diagram of different methods of sawing logs into lumber with cant sawing showing the removal of rounded edges in order to cut flat boards from the log. "Wood: Log-Sawing Patterns," Encyclopedia Britannica, Inc., http://www.britannica.com/EBchecked/media/55256/Basic-log-sawing-patterns-Live-and-cant-sawing-may-be.

Figure 9. An examples of the sample slabs that were sent by Willmore Lumber Co. and were further processed into flat and curved samples to fit into the Weatherometer. Photograph by author.

3.2 Sample Preparation

The slabs of wood shipped from Idaho were further cut down in the fabrication lab of the University of Pennsylvania using a table saw and miter saw. Slabs were sawn into standardized rectangular sizes that measured 9 ¼" long, 1 ¾" wide, and ½" deep, removing the outer bark and creating a flat surface.

Figure 10. Miter saw used in the Fabrication Laboratory. Photographs by author.

Each of these longer pieces was divided into two samples; the pieces were not physically separated but divided by a shallow cut that was later filled with a small piece of neoprene (1 ¾" x 1/8" x 1/8") with epoxy so that the samples would be separate but would fit more securely in the sample brackets. The middle sections of the long wood samples fit with neoprene were covered by a metal channel between the windows in the specimen brackets during the weathering process and thus had no exposure to the spray or UV lamps.

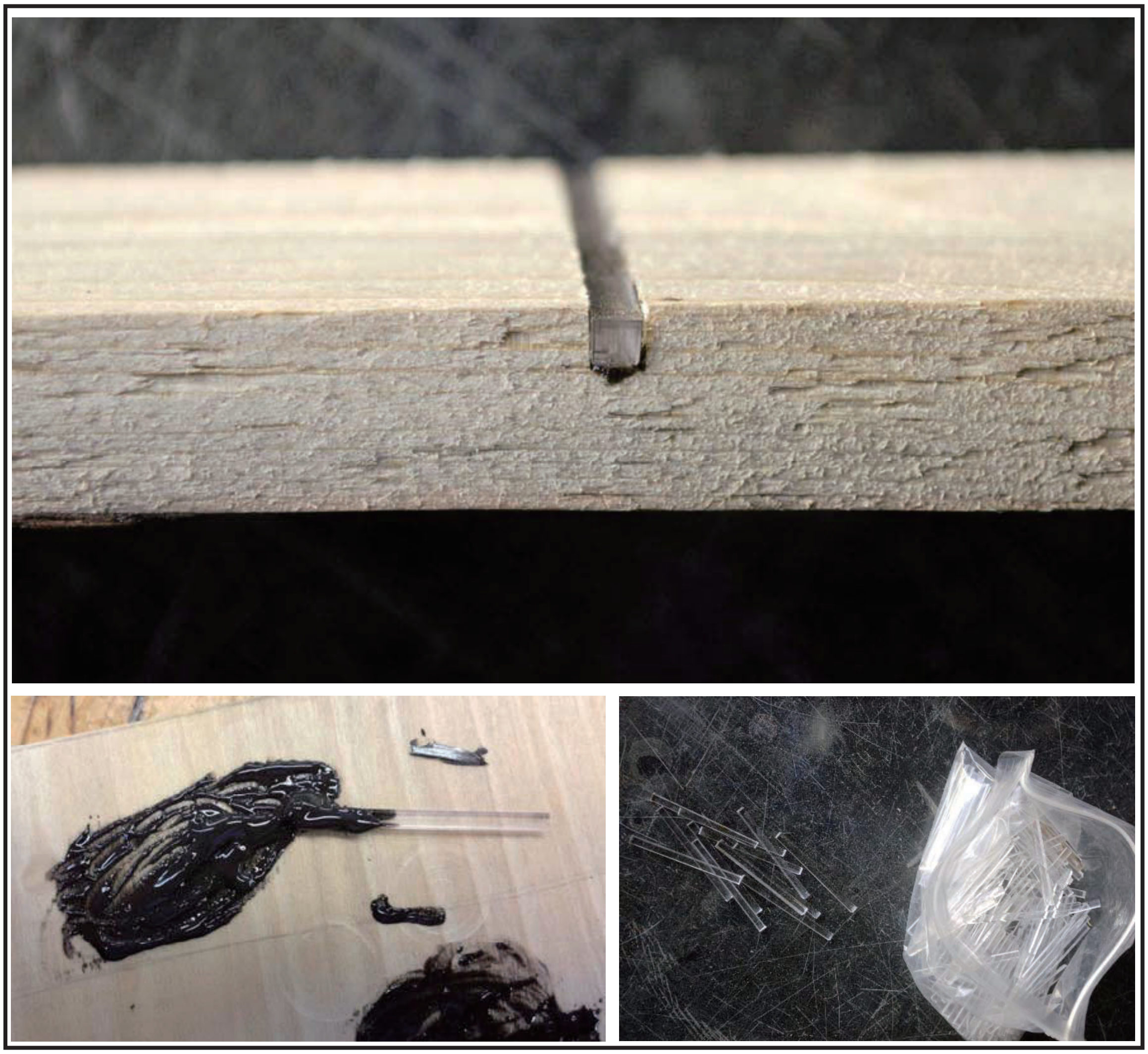


Figure 11. A sheet of neoprene was cut with a Universal Laser Systems laser cutter into small strips and inserted into a 1/8" deep cut between the smaller wood samples with J.B. Weld epoxy in an effort to separate the samples and prevent material from the top samples contaminating that on the bottom. Photographs by author.

ASTM Standard D7787/D7787M – 13, Standard Practice for Selecting Wood Substrates for Weathering Evaluations of Architectural Coatings, does not prescribe a specific size for testing wooden material, so samples were cut according to the needs for bracket preparation for the most efficient use of space in the Weatherometer. Additionally, though the wood found in situ on the log cabins has a rounded surface with some vestiges of bark that was mostly weathered off long ago, the bulk of the samples were cut flat and left with a slightly rough, un-sanded surface. This preparation was done to both allow the samples to fit more regularly within the brackets and to limit variables within the experiment that could strongly affect results, for wood is an incredibly variable material already without taking the curvature of samples into account.

In an effort to understand how curvature may affect results, samples of rounded surfaces were fit into brackets for qualitative comparison. These samples were of the same dimensions as the flat samples, but had not had their rounded tops removed by the saw. Instead, the bark was first removed by hand where possible, and then lightly sanded using a random orbit sander to achieve a surface without any vestiges of the bark, but still possessed the outermost layers of the wood.[2] In order to fit them into brackets (discussed below), these samples were milled along their ends and in their middles using a Bridgeport Vertical Mill so that the curved wood surface could sit proud approximately ½ - ¾” above the bracket surface, allowing full exposure to the conditions of the Weatherometer.

Figure 12. Example of a curved sample prepared for testing. This piece was ultimately not utilized in testing because of the extensive tracks left by wood borers on the surface. Photograph by author.

[2] The sanded surface may have had an impact on the absorption of the treatments because finely sanded surfaces more easily absorb products than un-sanded surfaces. This is considered in the conclusions section of this paper.

The flat samples to be used in the experiment were chosen from a sample pool of over sixty flat samples cut on the table saw. Each product and the control were tested in cohorts of six samples, so each sample bracket required three full-length pieces. Again according to the standard, wood samples were chosen so that they had the same characteristics relative to,

> (1) natural features of the wood such as the presence or absence of knots or knots of certain types and sizes, resin pockets, wood type (heartwood or sapwood) fragments of bark, pitch or juvenile wood, etc., (2) grain density, (3) grain orientation (for example, flat-grain or edge-grain, as well as orientation of the panel surface towards the pitch or bark of the log in flat grain sawn panels), (4) milling variations (smooth or rough sawn surface), and (5) chemical treatment, if any. (ASTM D7787/D7787M – 13, 6.5.3)

The smaller the wood samples, the more important these criteria are in replication of results. Without a fairly contiguous testing pool, the results do not carry much weight. All samples were cut with the same equipment and thus had the same milled variations, were from of the outer sapwood of the tree, and were sourced from old-growth pine with the same approximate grain density throughout. Any splits or knots were avoided in selection, as well as any widespread discoloration, for some of the samples possessed a gray-green sheen that would have affected color comparison results for weathering and product effect.

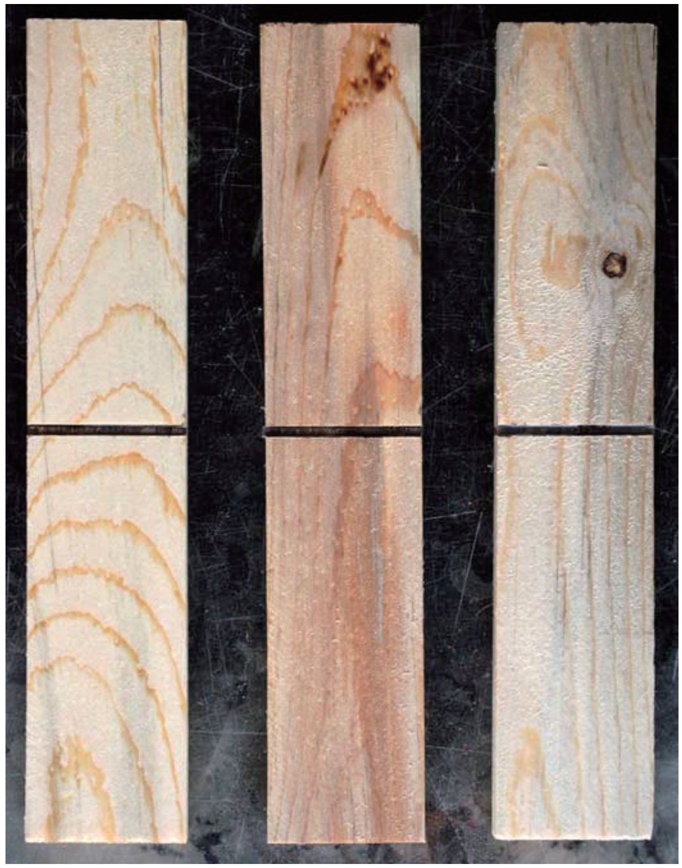


Figure 13. Examples of sample pieces that were not chosen for the experiment for various reasons. The left sample exhibits a grain orientation that was drastically different than most in the pool, the center sample exhibits both dark red-brown discoloration as well as a dissimilar grain orientation and what appears to be part of a knot, and the right sample exhibits a spike knot, gray discoloration, and differential grain orientation. Photograph by author.

Though all of the samples had the same tangential grain orientation because they derived from the same outside cut of the tree, the panel surface orientation was not always the same. This was due to both the extreme variability of wood as well as where the cut bisected the wood fabric in creating the panels. The panel surface orientations were taken into account in selection, but there was variability within the selections. Some of the examples of the common general orientations of the chosen samples are shown below:

Figure 14. ***Example 1:*** *The surface orientation of this panel captures the clear delineations of latewood and earlywood as the angle of cut bisects the curving rings of the tree. The cut edges towards being almost radial rather than tangential. Photographs by author.*

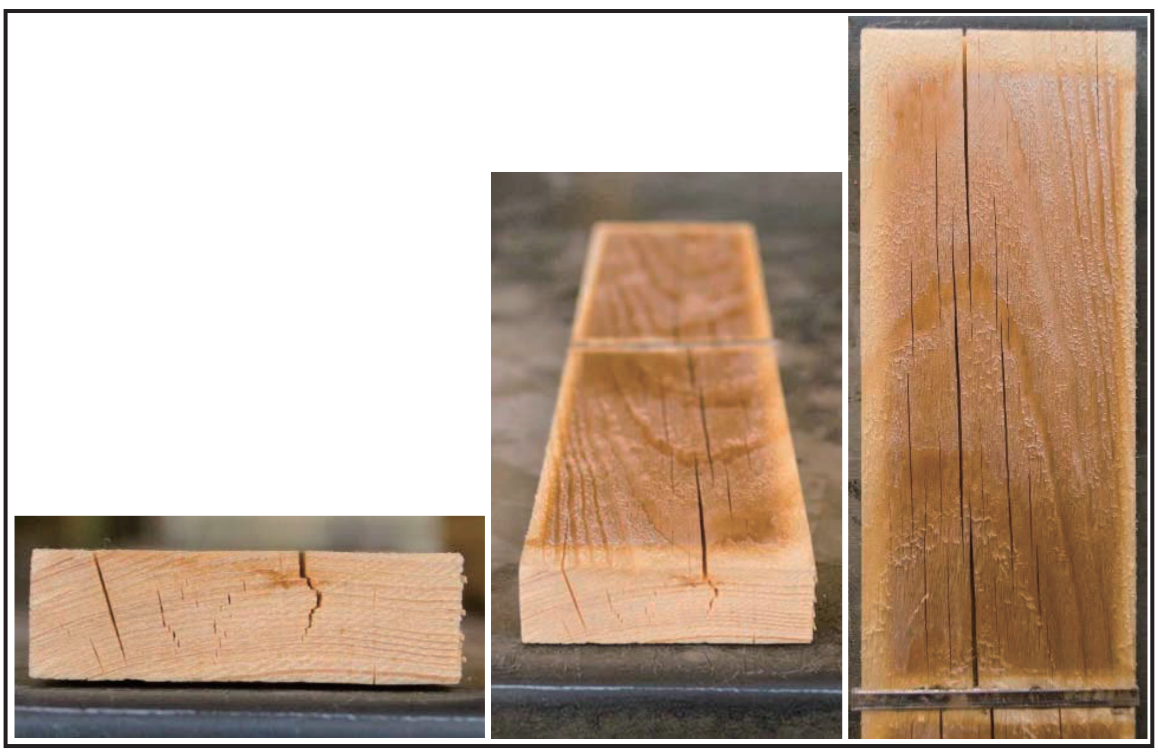


Figure 15. ***Example 2:*** *The surface orientation of this panel shows a U-shape pattern as the cut bisects the growth rings as they arch around the tree. Most panels are cut to this orientation. Photographs by author.*

Figure 16. **Example 3:** This surface orientation is a mixture of the previous two examples with the addition of a slight fabric abnormality from an event that occurred in the tree's life that may have caused the rings to waver, such as a knot from a branch formation or some sort of deformation. *Photographs by author.*

3.3 Bracket Preparation

In order to best fit the largest amount of samples into the QUV Weatherometer for testing, the large stainless steel specimen mount brackets specifically produced by Q-Lab were further retrofitted in the fabrication lab of the University of Pennsylvania to hold more than one sample. The large brackets measure 12 5/8" long x 6 ¼" wide x 5/8" deep with two window openings that measured 3 ¾" long x 7 7/8" wide. The smaller brackets measure 12 5/8" long x 3 ¼" wide x ½" deep with two windows openings that measured 3 ¾" long x 2 ½" wide. The large specimen brackets were retrofitted to hold three long sample pieces for cohorts of six samples per product per bracket while the small brackets were fitted to hold one long sample of the curved specimens holding one product on each sample. Due to the multiple amount of samples in each bracket as well as their depth[3], I determined that the best method of holding the samples in place was by installing posts which could support coated wires[4] for restraints.

The specimen brackets were measured and marked in the proper placement for each post. The large brackets required six posts, three on the top and three on the bottom, while the small brackets required four posts, two on the top and two on the bottom. The holes were created first with a punch and hammer on an anvil and then with a general international drill press fitted with a 1/8” twist bit. These holes were then given a bevel with a single-flute counter sink in order to allow the screw heads to lie flush to the bracket surface.

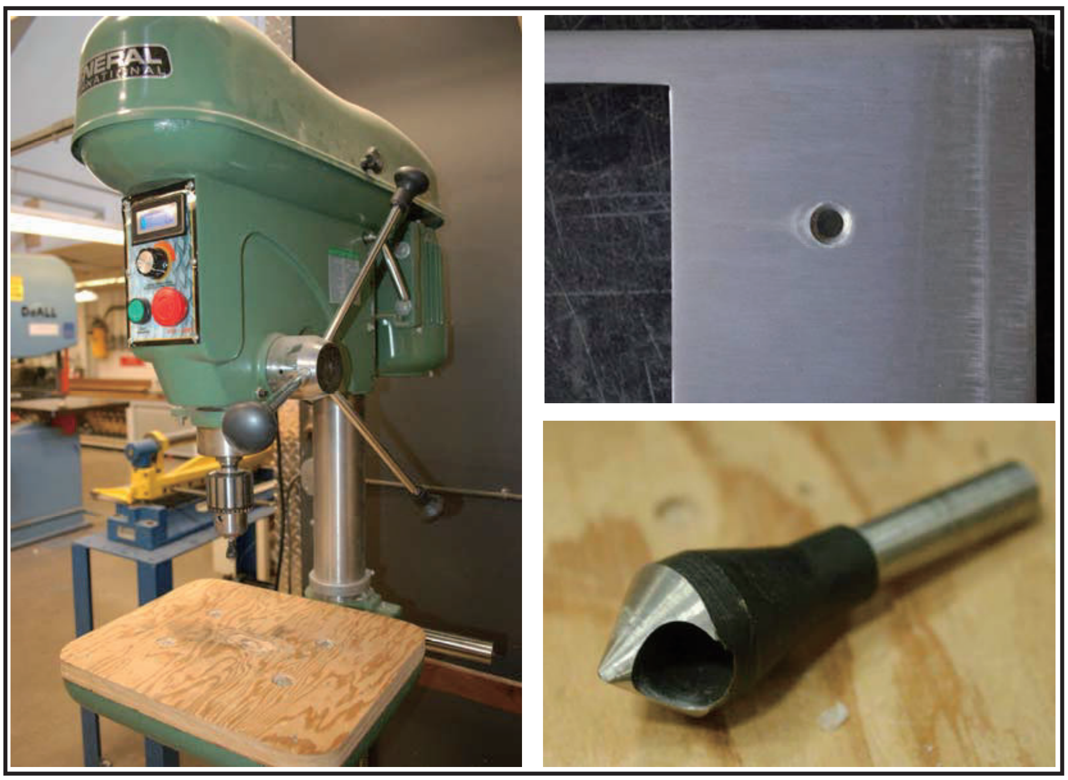


Figure 17. The drill press in the Fabrication Laboratory fitted with single-flute counter sink and the result on the specimen bracket. Photographs by author.

[3] The backs of the samples were almost flush with the back of the bracket. This was designed to allow for the proper cycles to occur within the Weatherometer. The distance between the backs of the brackets and the doors of the machine when closed is very small, only about ½ inch; if the samples made contact with the doors in the weathering process, then the condensation of the water on the samples would be affected. Instead of water condensing on just the front of the samples, contact with the doors of the machine would cause water to gather on the backs of the samples as well, affecting results.

[4] Underwriters Laboratories Inc. communications cable E-105765-C, No. 1029. Plastic coated wires were used to minimize any deterioration and subsequent staining.

Chicago Binder Posts, colloquially known as “sex bolts,” were then fitted through the drilled holes so that the posts faced the back of the brackets and could act as anchors for the wire.

Figure 18. Chicago Binder Posts fit into the large specimen brackets. Photographs by author.

In a further effort to prevent cross contamination between samples during accelerated weathering, sections of aluminum T-bar were cut with a band saw and milled using the Bridgeport Vertical Mill.[5] Two of these T-bars were fit into each bracket between the samples and were flush with the surface, covering ¼” on each of the top sides of the sample; additionally

[5] The T-bar sections were 8 ½” long and ½” deep with flat tops that were 5/8” wide.

the bottom of the T-bar extended ½” deep, separating the sides of the samples from any contact and subsequent cross-contamination. The curved sample brackets had only one T-bar separating the sample from a coated piece of wood that served to help fill the rest of the small bracket window. The coated and cured samples were weighed and finally inserted into the prepared brackets with the T-bars and long pieces of 1/8 inch thick neoprene to keep the samples in place; these materials were secured by coated wire before being placed into the racks of the Weatherometer. Each flat sample had an exposed area of approximately 8.28 sq. in. (2.21” wide x 3.75” long) while each curved sample had an exposed area of approximately 6.56 sq. in. (1.75” wide x 3.75” long).

Figure 19. Assembly of the large brackets with flat samples, T-bars, neoprene, and coated wire shown from the back, front, and in the final specimen bracket to be exposed to weathering.

Figure 20. Assembly of the small brackets with curved samples, T-bars, coated wood filler piece, and coated wire shown from the back and in the final specimen bracket to be exposed to weathering. Photographs by author.

3.4 Product Selection

In the selection of products for testing, a variety of considerations had to be taken into account. Due to the previously discussed conditions of the intended sites, desired treatments should ideally protect the wood from water infiltration, ultraviolet degradation, and have a long working life. These products also should be environmentally safe with limited toxicity and low levels of volatile organic compounds (VOC's). Additionally, the treatments ideally should be reasonably priced and accessible. In order to ensure quality control, only proprietary products were surveyed for the modern treatments rather than those that had to be prepared by a technician in the field.[6]

Product selection was further complicated by the conservation approach to the problems facing the log structures. Not only is the efficacy of the treatment important, but the reversibility and aesthetic quality of the treatment is significant as well. How the product and the treated wood weather over time, especially new wood replacements, is a major consideration for uniformity of appearance. If the surface of the replacement logs remains the bright white-yellow of newly exposed pine, then the fabric will never effectively fit in with that of the dark brown or silvered historic wood. However, in the world of contemporary wood protection, this lack of color change is often a goal. Most homeowners, the largest demographic of customers to which the commercial coating manufacturers are catering, want their homes and decks to remain as pristine as the day they were installed with minimal effort. In an effort to meet this expectation, a wide variety of products of different opacities and colors are available so that the client can start with the desired color and ideally remain at that level of color. In accordance with this ideal, treatments with light pigmentation to impart a darker surface that

[6] Thus, many of the newer ultraviolet protective technologies mentioned in the literature review that have not yet been utilized by coatings manufacturers in widespread treatments were not considered.

may match the weathered surfaces while also giving protection to the wood fabric were considered. The pigmentation in these products also has the added benefit of offering higher ultraviolet protection by literally blocking the sun's rays from reaching the wood fabric. However, any products with high enough pigmentation to become film-forming, generally anything more opaque than a semi-transparent stain, were not considered. Chosen pigmented treatments will also be tested on weathered wood in follow up natural weathering testing this summer to see how the wood might be affected aesthetically both initially and over time.

Due to limitations in the size of the machine, the testing pool was limited to seven products, two traditional and five commercial, along with a control. In an effort to gather a large pool of effective treatments to choose from out of the hundreds of products available to the wider public, I consulted with the National Park Service staff in Grand Teton National Park to see what products were currently being used on their historic log structures as well as with practicing professionals. Additionally, reputable online forums recommended by experienced professionals were reviewed to get a better idea of what products were the most popular, performed the best against certain decay mechanisms, and were the most available.

Two traditional treatments were chosen for testing. Because an oil finish had been historically applied to the logs on site at the Bar BC Dude Ranch and likely on other buildings in the area, boiled linseed oil was tested as a traditional finish and the Allbäck brand was used because it is currently utilized by the National Park Service. The boiled variety was used because it will dry and not leave a sticky residue that attracts dirt and soiling, unlike raw linseed oil. The other historically-used waterproofing treatment tested was a paraffin wax melted in mineral spirits, derived from a recipe often mentioned for wood protection by experts at the Forest Products Laboratory of the US Department of Agriculture (Feist, 1984; "Preparing A Non-Toxic Water-Repellent Preservative"). These recipes often include linseed oil or a varnish as an additive to the recipe, but for the purposes of this experiment, only paraffin wax and mineral spirits were used.

Commercial products are proprietary and do not divulge their formulations for reasons of trade secrecy and competition, but some key information such as class of coating, solvent type, percent solids by weight, and hazardous materials are available along with other logistical information in technical data sheets and material safety data sheets. In the process of selection, some of the standards were deemed more important than others depending on the needs of the site. Due to the high UV radiation in the Rocky Mountains, ultraviolet protection for the wood is a paramount concern; additionally, due to the decay mechanisms caused by high moisture content, water repellence was also prioritized. Also, because the coatings of such regional log structures in the past were historically clear or only lightly colored, selected products had to be as such with very little impact on the aesthetic appearance of the wood, but still allow new repairs to appear contiguous with the structure and to weather much the same as the historic material. Another important consideration is the changing product market due to increasingly strict laws on volatile organic compounds, or VOC's, from the enforcement of the Clean Air Act. States such as California have increased their restrictions past the federal limits, requiring that products have 250 g/L or less of volatile organic compounds in clear and semi-transparent stains while the federal limits require 550 or less. While Wyoming has no state limits, federal limits may change swiftly in the future causing higher VOC products to become illegal and are no longer available. Other criteria were considered in final selection, but those previously mentioned were deemed the most important.

In selection, there was an effort to test different kinds of treatments, oil- versus water-based, but efficacy was also incredibly important and many waterborne treatments were deemed ineffective by experts across the board. Therefore, most of the commercial treatments selected were reputable oil-based products, many formulated to low VOC, with the addition a promising waterborne treatment that emphasizes new nanotechnology-based protection. Table 2 below shows a basic comparison of each chosen product, and information on each product follows in the product application section. Material Safety Data Sheets (MSDS) and, for certain products, Technical Data Sheets (TDS) can be found on each product's website. Samples of these commercial products were generously donated by many of the manufacturers for testing purposes.

	UV Protection	Water Repellence	Pigmentation	Color	Base	VOC content	Biocidal / Fungicidal	Availability & Cost
Allbäck Linseed Oil	None	Yes	None	Lightly yellow tint	Oil	None	No	Sweden or New York supplier ($21.50/L)
Paraffin Wax with Mineral Spirits	None	Yes	None	Clear	Mineral spirits	772 g/L (low odor) 276 g/L (odorless)	No	Widely available (wax $4.42/lb) (spirits $16.44/gal)
DEFY Extreme Wood Stain	Zinc oxide Nanoparticles	Yes	Yes, fine white nano particles	Clear	Waterborne	Less than 250 g/L	Yes	Available at certain retailers or on the web ($42.71/gal)
Armstrong Wood Stain, Natural	Yes	Yes	Yes	Natural tone, lightly tinted	Oil-based	No more than 50 g/L	Yes	Available at certain retailers or on the web ($36.95/gal)
TWP 1500, Natural	Yes	Yes	Yes	Natural tone, lightly tinted	Oil-based	350 g/L	Yes	Available at certain retailers or on the web ($37.99/gal)
Flood CWF UV-5, Clear	Yes	Yes	Yes	"Clear" tone, lightly tinted	Oil-based (linseed)	332 g/L	Yes	Widely available ($18.98/gal)
Messmer's UV Plus, Natural	Yes	Yes	Yes	Natural tone, lightly tinted	Oil-based	Less than 250 g/L	Yes	Available at certain retailers or on the web ($37.99/gal)

Table 2. Simplified comparison of important criteria between the final chosen products.

3.5 Product Application

The seven products were applied to the wood samples according to instructions given by the manufacturer. These instructions were found on the can as well as on the websites of each individual product. In the case of the linseed oil and paraffin with mineral spirits, further investigation was carried out on the historic application of these treatments in order to apply them with the best results. The samples were measured for moisture content using a Wagner MMC 210 Moisture Meter before treatment and all contained less than 10% moisture.[7] Product application was carried out a week before the samples were inserted into the machine to allow time for curing, especially for the oil-based products. Before the products were inserted into the brackets for weathering, a sample 5/16 inch deep was cut off the end of each samples and labelled for the purpose of comparison before and after accelerated weathering.

Figure 21. Preparation of samples on the lab bench. Photograph by author.

All of the products recommended that the wood be dry to allow deepest penetration as well as thoroughly clean of weathered material and any dirt or contaminants such as previous paints and stains. Many recommended cleaning the surface with another internally-produced

[7] The Wagner MMC 210 Moisture Meter is a surface contact meter that measures the dielectric properties of the wood up to ¾” in depth.

cleaner or renewer before application. This cleaning specification was not an issue with the new wood samples used in this experiment, but possible complications in applying this product to weathered surfaces will be considered in future natural weathering tests on site this summer or in further accelerated testing in the lab. The weathered material of the historic buildings cannot be removed for both the integrity and the aesthetics of the site and these products are not meant to be consolidants for weathered material. While weathered wood may more readily accept treatments because of its more decayed and open microscopic structure that allows the coatings to penetrate, differential penetration across the wood surface can cause a blotchy appearance. A larger amount of product will be needed to coat weathered surfaces due to the greater penetration. Additionally, some surface material that has been degraded from ultraviolet radiation will likely detach with the mechanical abrasion of the stain application. The application for each product as well as basic information about its properties follows[8]:

[8] For full step-by-step application instructions refer to Appendix A.

3.5.1 Allbäck Boiled Organic Linseed Oil

Figure 22. Allbäck Linseed oil and application to a test sample. Photographs by author.

Allbäck organic linseed-based products originate out of Ystad, Sweden, but can also be obtained in the United States from a retailer in New York. The company sells a variety of products ranging from linseed oil putty to paint as well as raw and boiled linseed oil. The boiled linseed oil product is a refined cold pressed linseed oil that has been degummed and filtered. The manufacturer recommends its use as surface protection on unpainted wood and varnished or painted wood surfaces; application of this product to surfaces painted with Allbäck linseed oil paint fairly regularly can renew surfaces and prevent chalking (“Linolja Kokt”). On untreated wood surfaces, boiled linseed oil can act as a conditioner, waterproofing agent, and a sealant once the oil has oxidized.

Although the instructions for the linseed oil suggested using infrared heat in order to help the product penetrate more deeply, this method was not used because it was deemed largely impractical for field use. If an infrared heat source could be taken into the field for application, however, it could provide better protection by greater penetration. The product was brushed on using a natural bristle brush and easily soaked into the wood surface, turning it a light yellow. After thirty minutes, much of the oil had been soaked up by the wood substrate, so another coating was added. Excess oil was wiped off with a cloth after an hour longer. The wood absorbed the oil readily, gaining an average of 1.72 g from pre- to post-treatment. The boiled linseed oil had a pleasant smell with no toxic odors. Any rags or paper towels used in the application of this and the other oil-based products were first rinsed with water and disposed of carefully to prevent combustion.

3.5.2 Paraffin and Mineral Spirits

Figure 23. The paraffin and mineral spirits treatment was prepared by combining measures of paraffin wax beads and low odor mineral spirits at a very low temperature in a water bath on a hot plate. Photographs by author.

The paraffin wax beads and Sunnyside Low Odor Mineral Spirits were both sourced from McMaster Carr. Low odor mineral spirits still have a rather high VOC content, 772 g/mL, so in future experiments a low toxicity, no odor product should be utilized that has lower VOC's.[9]

The recipes for treatments involving mineral spirits with paraffin wax are usually produced in large volumes suitable for coating buildings or other outdoor wooden elements such as fencing, enclosures, etc. In these recipes, an already a small amount of wax is melted into a large amount of spirits, but in the reduction of the volume to a manageable size for the lab environment, i.e. less than the 1400 mL limit of the largest beaker in the lab, a miniscule amount of paraffin was used, only 0.39 g in 760 mL of mineral spirits. The mixture was kept

[9] For example, Klean-Strip Green Odorless Mineral Spirits have 65% less VOC's, about 226 g/mL.

warm for application onto the wood sample surfaces and it was applied heavily as advised; five coats of this treatment were added over the period of an hour.

Table 3 at the end of this section displaying the amount of product taken on by each sample indicates that generally only a small amount of paraffin was deposited on each sample, 0.71 g on average, and that the amount taken in varied greatly between each piece from 0.19 g to 1.19 g. In future testing with this treatment, a larger volume of the product might be produced for a lower potential source of error.

3.5.3 DEFY Extreme Exterior Clear Wood Stain

Figure 24. DEFY Extreme clear wood stain had a milky white appearance but the body of the treatment was thin and applied almost clear. Photographs by author.

DEFY Extreme Exterior Clear Wood Stain was especially intriguing both because of its water base and very low VOC content, less than 250 g/mL, as well as the nanoparticle technology that it aggressively advertises. The product is a acrylic-resin, semi-transparent wood stain that uses nanotechnology to purportedly impart a greater level of durability to the wood. This product uses nano-sized zinc oxide particles, advertised to be distributed at a rate of over 30 trillion particles per square inch, to both shield against UV radiation with little to no color change as well as protect against mold and mildew. It is designed to be used both on interior as well as exterior wooden surfaces and dries to a flat, semi-transparent finish that allows the natural wood grain to show through. It appears fairly easy to maintain, the manufacturer recommends washing with a mild detergent to clean dirty or dull surfaces and cleaning with DEFY Wood Brightener before reapplication of the stain annually. It comes in a range of light colors, but the clear tone was chosen in an effort to see how the zinc oxide particles performed without the assistance of colored pigmentation ("DEFY Extreme Wood Stain").

The stain was extremely thin due to its water base and had to be stirred often to ensure that the particles stayed in suspension throughout application. As a result of the water base, the product barely had any odor or fumes. The application instructions called for a synthetic bristle brush. The product brushed on easily and dried quickly, not causing much of a color change except for a light white sheen. The product appeared to soak in within twenty minutes, so another coat was applied while the first was still wet. Excess coating was avoided, however, in order to avoid film-formation on the surface, in accordance with a warning issued by the manufacturer on the label. The wood samples appeared to have absorbed a fairly large amount of the product, with an average weight change of 1.25 g pre- and post-weathering.

3.5.4 Armstrong's Wood Stain for Decks (Natural Tone)

Figure 25. Armstrong's combination oil treatment appeared dark in the can but had a translucent appearance on the wood. Photographs by author.

Armstrong's Wood Stain for Decks is a semi-transparent stain for wood produced in California and contains a high oil content. The base is a mixture of drying oils and nondrying conditioning oils so that the product attains a deep penetration but still retains a dry to the touch exterior barrier from the drying oils; the nondrying oils are meant to replace the natural oils in the wood that were lost, rejuvenating the substrate. These oils and their fairly slow drying time allows for the product to be left on the surface overnight before wiping away excess, causing greater product penetration; the wood samples for this product gained the most weight, an average of 2.0 grams post-treatment. Additional elements in the formulation include vegetable oils, transparent-oxide pigments, water repellents, mildewcide, and solvent. The Armstrong-Clark Company makes it clear that they do not use titanium dioxide particles in their products, just transparent oxide and earth colors for a sharper color. Additionally, solvent content is extreme low, under 50 g/mL, making this treatment the most environmentally friendly of the commercial selections. The product comes in three shades: Natural, Cedar, and Redwood; for this experiment, Natural Tone was used ("Oil Based Wood Stain").

The Armstrong stain looked very dark upon first inspection, but was actually fairly light and more yellow, likely from the variety of oils that are the basis of this product, when brushed onto the wooden surface. No specification was given for brush type, so a natural bristle brush was used and the product spread very easily across the surface. The oils were very fluid so this product bled easily down the sides and underneath the sample, coating most of the surface. The product was absorbed within the first 30-60 minutes of application, so another coat was added and allowed to soak in overnight. The excess product was wiped off of the surface the next day, as per specifications.

3.5.5 TWP 1500 Natural Stain (Natural Tone)

Figure 26. The sample from TWP came in a small bottle that was easily mixed via shaking. Left photograph by author, right photograph: http://www.twpstainhelp.com/how-to-apply-twp-1500-stain/.

TWP, or Total Wood Protection, 1500 Series is a penetrating semi-transparent stain that is billed as being specifically designed to penetrate better and outperform their previous 500 Series stain. It is an EPA approved wood enhancing preservative, with a VOC content of 350 g/mL, which protects against structural and surface damage as well as water infiltration and mold growth. The product also claims to have unique UV absorbing technology that prevents unwanted graying and color changes. The stain comes in range of natural tones that are easy to apply and maintain (“TWP 1500 Stain”).

The TWP stain came in a small bottle that showed that a good deal of pigment settles at the bottom when not mixed fairly often. The specifications did not call for a certain kind of brush, so a natural bristle brush was used to coat the wood sample. The coating was very light and easily spreadable, soaking into the wood almost immediately. Another coat was added, as per instructions, within the first thirty minutes of the first to keep a wet on wet application for consistency. The stain was fairly dark, though it is the lightest of the stains that total wood preservation sells. The product appears to either be very light or to not penetrate as deeply as advertised because the average weight change between pre- and post-treatment was only 0.96 g.

3.5.6 Flood CWF-UV 5 Penetrating Wood Finish for Fences, Decks, and Siding (Natural Tone (Clear))

Figure 27. Flood's product had an orange, milky appearance in the can and applied in a fairly translucent manner. Photographs by author.

Flood CWF-UV 5 is an oil-based finish that adds minimal color and highlights natural wood grain and resists mildew. The Flood manufacturer, Akzo Nobel Paints, appears to be very protective of the formulation, using trademarked terms for chemicals in the product. It contains a copyrighted chemical deemed Penetrol that is supposed to help the stain penetrate and protect wood from the inside out, ensuring long-lasting performance; additionally, the Climate Guard Technology is intended to provide outstanding rain and sun protection. Product overviews imply, however, that the UV protection derives from transparent iron oxides. It has a fairly low VOC content at 332 g/mL. This stain comes in a range of tones, though the selection color is labelled as their clear tone (“Beautiful, Easy Stain”).

The UV product produced by Flood was of a very thick, light orange-brown consistency. The instructions recommended thorough stirring of the product throughout the application period to keep the mixture homogenous, and additionally called for the use of a synthetic bristle brush rather than a natural brush. The product brushed on easily, but appeared fairly thick and more orange than the surface of the wood. It appeared to absorb quickly, within the twenty minute re-coating time frame laid out in the application directions, so another coat was added before the first dried fully. Total product retention appeared fairly small, however, on average 0.86 g.

3.5.7 Messmer's U.V. Plus Exterior Wood Finish (Natural)

Figure 28. Much like Armstrong's product, the oil-based product by Messmer's appeared dark in the can but applied in a translucent layer with light pigmentation. Photographs by author.

Messmer's UV Plus Wood Stain, a product out of Utah, is a penetrating stain and oil finish meant for a variety of exterior wood surfaces that "beautifies and protects exterior wood, providing a natural appearance" ("Messmer's UV Plus"). The product contains UV absorbers (transparent iron oxides) and fungicides and comes in a range of tones and semi-transparent colors. It does not form a film on the surface when properly applied and the product literature claims that it can be simply reapplied as necessary after the wood surface has been cleaned or brightened without stripping or sanding; it can also be applied over other penetrating finishes as long as the previous finish has been sufficiently weathered to allow penetration, it should not be applied over film-forming finishes, however. The manufacturer estimates the product life to be from 3-4 years on rough vertical surfaces, though conditions can cause results to vary ("Messmer's UV Plus"). The product has a very low VOC content, less than 250 g/mL, and thus is compliant even in states with strict laws like California.

The finish appeared fairly dark in the can; however, once the product was mixed and the product brushed onto the wood, the finish was translucent with some light brown pigmentation. The directions called for the use of a quality bristle brush and the oil-based stain was easy to apply. The wood easily absorbed the first coat of stain within twenty minutes, so another light coat was brushed onto the surface. Weights before and after treatment indicate that on average the wood absorbed 1.08 g of the stain. After the 30-45 minute time period specified in the instructions, excess stain was wiped off of the surface with a cloth to prevent film formation on the surface.

The amount of product absorbed by the samples is recorded in table 3. Each long sample was weighed with an Adventurer OHaus Analytical Balance before and after treatment; the difference in weight is a good approximation of the amount of treatment that the wood substrate took in. The treated samples were weighed right before weathering, so the products had time to cure, and solvent to evaporate, before weighing.

	Weight (Pre-Treatment)	Moisture Content (for each sample)	Weight (Post-Treatment, Pre-Weathering)	Mass of Treatment Absorbed
Control				
CON-1 & CON-2	72.77	8.9 / 8.4	72.77	n/a
CON-3 & CON-4	70.27	8.0 / 7.6	70.27	n/a
CON-5 & CON-6	74.46	8.9 / 8.9	74.46	n/a
Linseed Oil				
LIN-1 & LIN-2	73.09	8.5 / 8.3	74.93	1.84
LIN-3 & LIN-4	62.28	7.2 / 7.8	64.45	2.17
LIN-5 & LIN-6	76.56	9.5 / 9.5	77.71	1.15
Paraffin and Mineral Spirits				
PAR-1 & PAR-2	76.41	8.2 / 8.7	77.18	0.77
PAR-3 & PAR-4	63.82	7.5 / 7.1	65.01	1.19
PAR-5 & PAR-6	76.67	9.8 / 9.6	76.86	0.19
DEFY Extreme				
DEF-1 & DEF-2	76.87	7.6 / 8.1	78.22	1.35
DEF-3 & DEF-4	60.57	7.3 / 6.9	62.15	1.58
DEF-5 & DEF-6	66.75	7.9 / 8.5	67.57	0.82
Armstrong's Wood Stain				
ARM-1 & ARM-2	74.30	8.9 / 9.5	76.02	1.72
ARM-3 & ARM-4	73.28	8.0 / 7.8	75.51	2.23
ARM-5 & ARM-6	79.13	9.1 / 8.7	81.18	2.05
TWP 1500 Natural				
TWP-1 & TWP-2	58.01	6.8 / 6.6	59.27	1.26
TWP-3 & TWP-4	73.01	8.6 / 9.0	73.87	0.86
TWP-5 & TWP-6	73.83	7.9 / 8.4	74.59	0.76
Flood CWF UV-5				
FLO-1 & FLO-2	76.11	8.7 / 9.2	77.21	1.10
FLO-3 & FLO-4	72.84	9.7 / 9.8	73.72	0.88
FLO-5 & FLO-6	78.66	9.8 / 9.8	79.27	0.61
Messmer's UV Plus				
MES-1 & MES-2	68.68	7.9 / 8.4	69.56	0.88
MES-3 & MES-4	66.74	7.6 / 7.3	67.88	1.14
MES-5 & MES-6	67.88	7.3 / 7.3	69.10	1.22
Curved				
LIN-CURV & FLO-CURV	88.94	6.3 / 7.1	90.43	1.49
PAR-CURV & AND DEF-CURV	96.58	5.2 / 6.3	96.70	0.12
ARM-CURV & TWP-CURV	91.43	8.9 / 8.9	91.39	0.04
CON-CURV & MES-CURV	109.24	6.0 / 6.2	109.54	0.30

Table 3. Weight measurements before and after treatment. The difference in weights indicates how much product each grouping of samples may have absorbed.

3.5.8 T-test

The paired (dependent) t-test was used to compare the mean weight of each sample cohort by comparing the initial weights before and after treatment. The values were calculated using a data analysis plug-in on Microsoft Excel[10], but the calculations are based on the equation:

$$t = \frac{\overline{x_1} - \overline{x_2}}{\sqrt{\frac{s_1^2 - s_2^2}{n}}}$$

$\bar{x}_1$ = mean of the first sample

$\bar{x}_2$ = mean of the second sample

s_1^2 = variance (squared standard deviation) of data set 1

s_2^2 = variance (squared standard deviation) of data set 2

For all samples the t critical value exceeded that of the t stat value at the 95% confidence interval at 5 degrees of freedom. Thus, the null hypothesis was accepted, indicating that there was not a difference between the weights of the samples before and after treatments.

[10] Calculations can be found in Appendix G.

Sample		Weight Change after Treatment
Control	t Stat	0
	t Critical	2.91998558
	pass / fail?:	**pass**
Linseed Oil	t Stat	-3.254901961
	t Critical	6.313751515
	pass / fail?:	**pass**
Paraffin and Mineral Spirits	t Stat	-1.38
	t Critical	6.313751515
	pass / fail?:	**pass**
DEFY Extreme (Clear)	t Stat	-3.157894737
	t Critical	6.313751515
	pass / fail?:	**pass**
Armstrong (Natural)	t Stat	-23.77777778
	t Critical	6.313751515
	pass / fail?:	**pass**
TWP 1500 (Natural)	t Stat	-16.2
	t Critical	6.313751515
	pass / fail?:	**pass**
Flood CWF UV-5 (Natural)	t Stat	-5.518518519
	t Critical	6.313751515
	pass / fail?:	**pass**
Messmer's UV Plus (Natural)	t Stat	-29.5
	t Critical	6.313751515
	pass / fail?:	**pass**
Curved Samples	t Stat	-1.289804043
	t Critical	2.91998558
	pass / fail?:	**pass**

Table 4. T-test values for the weight change before and after treatment.

3.6 Accelerated Weathering

Accelerated weathering was conducted using a QUV Weatherometer in the Architectural Conservation Laboratory (ACL) at the University of Pennsylvania. The machine is designed to reproduce the damage caused by sunlight, rain, and dew so that in a few days or weeks it can reproduce the damage incurred over months and years of outdoor weathering. Materials are exposed to alternating cycles of UV light and moisture at controlled, elevated temperatures using heating elements, special fluorescent UV lamps, condensation humidity, and water spray nozzles (“QUV Accelerated Weathering Tester || Q-Lab"). Accelerated weathering by nature is an extreme process because of the small cycles of wetting and drying along with the very high levels of ultraviolet radiation; additionally, the environment in the machine does not always resemble that found in the climate where the materials will actually weather. Therefore, natural weathering testing is always recommended in the field to evaluate results found in the laboratory.

Figure 29. The QUV Weatherometer in the Architectural Conservation Laboratory both closed (left) and opened with specimen brackets inserted (right). Photographs by author.

The Weatherometer measures 54” long x 21” wide x 53” high; the chassis and cabinet are both constructed of stainless steel and aluminum to prevent rusting. The normal capacity of the machine is forty-eight samples, twelve small brackets on either side holding two samples apiece. In this experiment, however, eight large brackets were retrofitted to hold six flat samples apiece and the small brackets two apiece, for a total sample population of fifty-six. These specimen brackets were faced inwards for exposure of the surfaces to the bulbs and spray.

Twelve spray nozzles, six on each side of the machine line the inside of the machine facing outwards toward the sample brackets to serve as both an erosion source as well as a thermal shock. Water sourced for the spray and condensation cycles was tap water rather than deionized water, so there is a possibility that impurities in the water may have had a slight impact on the results. However, the pan and brackets were fully cleaned with acetone before testing to ensure that there were no encrusted contaminants from past weathering tests.

In order to ensure that the test specimens were weathered as evenly as possible, the brackets were rotated clockwise through the machine by one slot every 100 hours when the samples were being taken out for monitoring.

3.6.1 Cycle Selection

The machine is designed so that cycles and their intensities can be modified according to the given experiment in order to best predict the behavior of a material in a given environment; however, this prediction is an inexact science and natural weathering should be used for confirmation. A twenty-four hour timer dial on the machine allows cycle programming through tabs of fifteen minute increments; tabs flipped outwards set the machine to the ultraviolet setting while tabs flipped inwards indicate the condensation cycle.

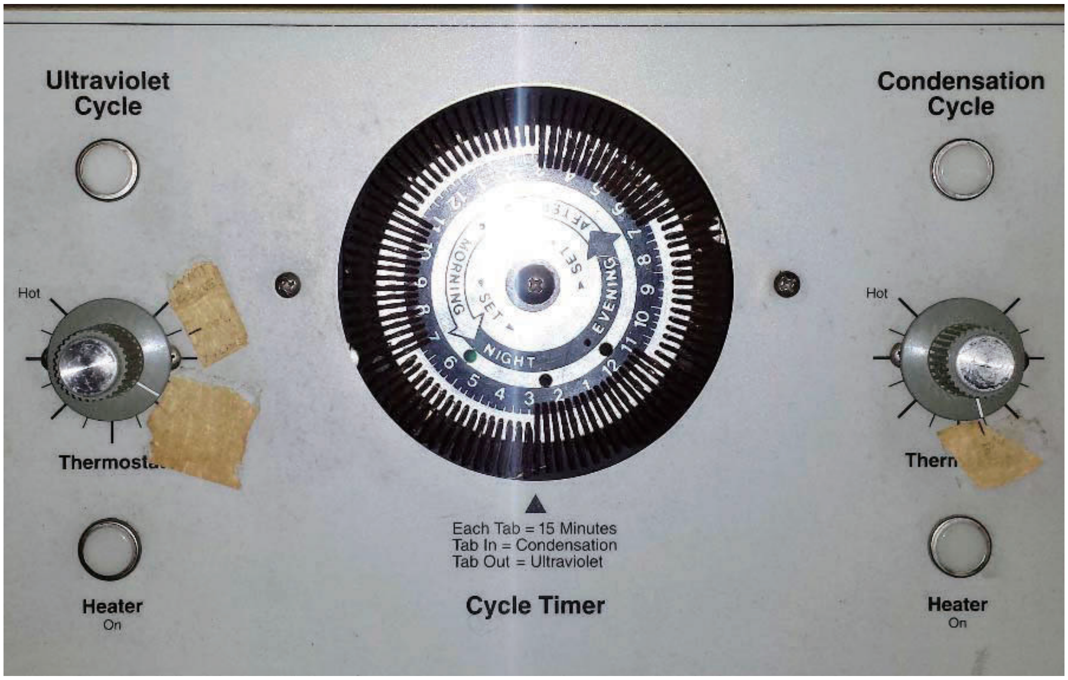


Figure 30. The control panel of the Weatherometer, displaying the cycle selection dial as well as the dials for controlling temperature of both the Ultraviolet cycle as well as the Condensation Cycle. Photograph by the author.

Temperatures during these cycles can be set to preferences as well and be maintained by a black-panel sensor. Ultraviolet temperature is usually set to either 50˚C (122˚F), 60˚C (140˚F), or 70˚C (158˚F); in this experiment, the temperature for the UV cycle was set to 60˚C, though the temperature panel usually indicated that the machine remained around 63˚C. The temperature for condensation is usually set at either 45˚C (113˚F) or 50˚C (122˚F); the temperature was set to 50˚C for the condensation cycle of this experiment. The air blower in the machine serves to rapidly cool the chamber at the beginning of the condensation cycle, for the first fifteen minutes, in order to thermally shock the samples and cause water vapor to condense on the surfaces of the samples. Additionally, the spray can be set to three different modes: spray for a few minutes at the beginning of the condensation cycle for thermal shock, spray for the whole period rather than condensation for more erosion, and no spray, just condensation. The cycle was set to the first option, spray for five minutes at the beginning of the condensation cycle for both thermal shock and erosion (*QUV Accelerated Weathering Tester*, 1993).

The weathering cycle in this experiment derived from a set of typical cycles used the in operation of fluorescent lamp devices which recommends for UV-B 313 lamps at 0.63 irradiance and 310 nm wavelength, cycles of four hours UV exposure at 60 ± 3˚C and four hours condensation at 50 ± 3˚C (Wypych, 2008). The QUV Weatherometer was set to a four hour condensation cycle with the aforementioned five minute spray at the beginning of the cycle for thermal shock and erosion. The samples were then exposed to four hours of ultraviolet radiation before undergoing the spray and condensation again in the cycle. This results in rapid cycles of wetting and drying, heating and cooling, and abrasion that stress the wood fabric and coatings to their mechanical limits.

3.6.2 Light Source

There are different types of UV lamps that can be used in the QUV Weatherometer that emit different wavelengths of radiation. They are generally categorized as UV-A (315-400 nm) or UV-B (280-315 nm) and all of these bulbs produce generally ultraviolet light with a small amount of visible and infrared as well. In this experiment UV-B-313 lights were utilized because they give a substantially higher UV output than the other lamps which accelerates the degradation of the materials in the machine even more. The peak emission of the UV-B lamps is at 313 nm. Additionally, the shortest wavelengths of the UV-B region are responsible for most polymer damage, and thus these lamps are the most frequently used in stimulating the damage caused by direct sunlight, especially in determining differences in generically similar formulations in coatings. Though UV-B lamps are more intense and have less correlation to natural weathering than UV-A lamps, the purpose of the experiment was to push the wood and the UV resistant treatments to their limits to see how they might break down under extreme circumstances (*QUV Accelerated Weathering Tester*, 1993).

The Solar Eye Irradiance Control on the QUV panel allows for the machine to adjust the irradiance of the UV lamps to the temperature of the machine. UV lamp outputs vary with temperature shifts, radiating less light at higher temperatures. Thus, QUV Weatherometers without the irradiance control give difference irradiance at each different exposure temperature. Though this is not a dire problem because higher temperatures accelerate degradation as well, stabilized UV irradiance is preferable. The irradiance controls were therefore set to the Q-Panel's given recommended settings: 0.63 for UV-B 313 lights at 60˚C. The maximum settings for the highest degradation with UV-B 313 lamps is much higher at 1.10, but the manufacturer strongly discourages pushing the machine close to this limit. At the beginning of the experiment, the UV lights were recalibrated with a CR10 Calibration Radiometer to ensure that the "actual irradiance" was the same as the "set point irradiance" shown on the panels (*QUV Accelerated Weathering Tester*, 1993).

3.6.3 Period of Exposure

The experiment was carried out over an 800 hour period in a QUV Weatherometer to come as close to industry standards for testing as possible with the limited amount of time available for testing. Another thesis student was also completing her research using the QUV Weatherometer, so exposure time for both experiments was cut short of the standard industry marks, usually at 1000 or 1500 hours. 800 hours of accelerated weathering with UV-B 313 bulbs which offer the most intense ultraviolet irradiance of QUV's products proved strong enough to sufficiently weather the wood samples and their coatings, however.

3.7 Testing Program

In order to monitor the changes that may have occurred at the surface of the samples during accelerated weathering in both the wood fabric and the penetrating treatment, a variety of testing methods derived from ASTM standards were utilized to test for certain properties of the wood. Many methods stemmed from past papers testing the properties of wood, mentioned in in the literature review section of this thesis.

3.7.1 Ultraviolet Resistance

As explained in the literature review chapter of this thesis, ultraviolet radiation can cause degradation of wood surfaces through the deterioration of the amorphous lignin material in wood that holds the cellulose fibers together. The loss of this glue-like material causes the cellulose fibers to become largely unanchored to the rest of the wood substrate and therefore easily abraded and removed. Similarly, treatments that do not protect against ultraviolet radiation can also be altered chemically so that they fail to properly protect the wood. Changes in weight can effectively illustrate the loss of fabric due to the degradation and removal of wood surface and treatments. Additionally, these failures at the wood's surface manifest visibly through color changes, darker or lighter depending on the species of wood, and through roughening of the wood's surface, a result of loose cellulose fibers. These changes can also be monitored through chemical analysis such as Fourier Transform Infrared Spectroscopy (FTIR) for the loss of lignin as well as a loss of treatment at the surface.

3.7.1.1 Surface Inspection

Surfaces were inspected both before and after accelerated weathering using a Leica MZ16a Microscope and photographs taken with a Nikon DS Fi-1 Camera with NIS Elements BR

Software for comparison. The photographs were taken at both 1x and 10x magnification to get two different views of the wood surface for better characterization. Surfaces were inspected for both evidence of product in the wood fabric as well as degradation of the lignin and subsequent friability and separation of the cellulose fibers.

3.7.1.2 Weight Change

With ultraviolet degradation of the lignin and potentially of the treatments, the degraded lignin and cellulose on the surface of the samples become susceptible to removal by abrasion such as the water spray in the machine used to imitate driving rain. Samples were weighed to the nearest one-hundredth of a gram with an analytical balance before and after accelerated weathering once they had achieved similar moisture content to determine the extent of loss of fabric and/or product.

3.7.1.3 Color

Color change, either darker or lighter depending on the wood species, is a reliable visible indicator of a chemical change in the wood substrate. Perception of color can vary enormously depending on a variety of factors such as the viewer, light source, and surface texture. In order to alleviate these sources of error, a new handheld spectrophotometer, a Konica Minolta Spectrophotometer CM-2500d, was utilized for color measurements in the Architectural Conservation Laboratory. This piece of equipment measures color coordinates based on daylight illumination using the CIE 1976 L*a*b* system, an approximately uniform color space based on nonlinear expansion of the tristimulus values and taking differences to produce three opponent axes of lightness-darkness, redness-greenness, and yellowness-blueness. Color changes are indicated by ΔL*Δa*Δb*, ΔE* overall. ΔE* gives no indication of the character of the difference in color because it does not show the quantity and direction of the hue, chroma, and lightness changes, so all three color coordinates are just as if not more useful than the entire color change. This color system allows for the quantification of color change and a more accurate view of the physical change occurring at the surface of the wood upon accelerated weathering. ASTM D2244 – 14 – Standard Practice for Color Tolerances and Color Differences from Instrumentally Measure Color Coordinates was used as the standard for collecting color data and reporting the results.

3.7.1.4 Fourier Transform Infrared Spectroscopy (FTIR)

Fourier Transform Infrared Spectroscopy (FTIR) is an analytical technique that can be used to identify organic (and some inorganic) materials. This technique was used in this experiment both because it is utilized in a number of papers that assess chemical changes during weathering and because of a contact in the analytical lab at the Philadelphia Museum of Art who generously donated her time and resources for testing and analysis for free. Additionally, it requires microscopic samples of fabric for analysis and thus is almost entirely nondestructive. FTIR measures the absorption of infrared radiation by the sample versus the wavelength and generates absorption bands that identify the molecular compounds and structures. The bands are a measure of the excitation of molecules into higher vibrational states from the absorption of the IR radiation. The wavelength of light absorbed by a particular molecule is a function of the difference between the at-rest and excited vibrational states. Each molecule has a signature excitation pattern that is characteristic of its structure and can be used for identification. The machine uses an interferometer to modulate the wavelength from a broadband infrared source. A detector, in turn, measures the intensity of transmitted or reflected light as a function of wavelength; the computer analyzes the interferogram signal from the detector and transforms it into a single-bean infrared spectrum which is usually displayed a plot of intensity versus wavenumber (in cm^{-1}), the reciprocal of the wavelength.

For product identification, the generated infrared spectra are usually analyzed through comparison with the spectra of known materials from a material database. Matches can identify the constituents within a material. Bands in the range from 4000-1500 wavenumbers usually are the result of functional groups while bands in the 'fingerprint region', 1500-400 wavenumbers, are generally due to intramolecular phenomena and are highly specific to the material tested. Quantitative concentrations of compounds can also be determined from calculating the area under a curve in characteristic regions of the IR spectrum, but requires a standard curve from spectra for known concentrations ("Fourier Transform Infrared Spectroscopy (FTIR)").

In the case of this experiment, FTIR was used in an effort to compare wood surfaces before and after accelerated weathering. Because the exact contents of many of the commercial products remain unknown, qualitative rather than quantitative testing was performed to try to show the loss of lignin due to ultraviolent radiation in weathering. A variety of papers were consulted that examine the degradation of wood and its resulting IR spectra in order to determine standards of comparison for lignin loss (Lionetto et al., 2012; Proniewicz et al., 2002; Schmalzl and Evans, 2003). Additionally, each product-coated sample was also analyzed for a loss of lignin to determine if the coating was effective at ultraviolet degradation prevention.

3.7.2 Water Repellence

Water repellence is an important aspect of wood protection because it keeps the moisture content of the wood below the fiber saturation point, the point at which many deterioration mechanisms begin to occur. In order to determine if the accelerated weathering had an impact on the water repellent properties of each treatment, contact angle measurements were determined to be a reliable method. The approaches laid out in the following standards and experiments allowed for the results to be quantitative rather than just qualitative through angle measurements taken at the interface of the drop of liquid and the wood. ASTM D7334 – 08 - Standard Practice for Surface Wettability of Coatings, Substrates and Pigments by Advancing Contact Angle Measurements served as a standard for this test. Other papers were also consulted for good method in this procedure (Woodward, 1999; Lamour, 2010). Because a goniometer was not easily accessible, an experimental set up following the method and materials found in "Contact Angle Measurements Using a Simplified Experimental Setup" was created and found to be effective for photography of samples and measurements.

3.7.3 Treatment Retention

Fourier Transform Infrared Thermography was also used to determine if the wood surfaces retained their treatments during weathering. Bands and their relative intensities from before and after accelerated weathering were compared for qualitative analysis. Additional observation with the Leica MZ16a Microscope lent insight into the treatment retention of each product.

3.7.4 Product Performance

Samples were removed from the machine every 100 hours for photography and inspection in an effort to monitor the degradation of the material. The weights and colors of the samples were measured every period but the data fluctuated significantly depending on the point in the weathering cycle when the samples were removed from the machine. Thus, for these criteria, only before and after measurements, when the wood was at a similar moisture content, were deemed reliable. Inspection of the surfaces every 100-hour period, however, led insight into how each treatment behaved as time passed. Surfaces were monitored for symptoms of degradation such as surface roughening, checking, rising grain, and cupping according to terms in ASTM D9-12 Standard Terminology Relating to Wood and Wood-Based Products. Additionally, cohorts were evaluated within for the performance of individual samples as well as between the different treatments based on a variation index of a 1-5 scale, 1 being bad to 5 being excellent.

Chapter 4: Observations

4.1 Ultraviolet Resistance

The samples were analyzed using a series of tests and observations in order to better understand the degradation of the wood by ultraviolet radiation and how each treatment performed in relation to surface deterioration.

4.1.1 Surface Inspection

Wood surfaces as well as cured stains on glass slides were examined more closely at low magnification to examine changes that occurred during weathering, in the case of the wood samples, and to better understand composition, in the case of the stains. Photographs were taken at the same location before and after weathering for the most part. A full list of photographs taken with a Nikon DS Fi-1 Camera on a Leica MZ16a Microscope for the wood samples and on an Olympus CX31 Microscope for the stain samples is available in Appendix B. Examples from each treatment are expanded on below.

Control

Figure 31. Control Sample 4 before (left) and after (right) weathering at 1x magnification (above) and 10 x magnification (below). Photographs by author.

The control samples exhibited all of the signs of ultraviolet degradation, showing checks ranging in size from micro-sized, as seen in the 10x magnified image above, to rather large. Surfaces were visibly roughened and the fibers appear loose on the surface with less solid wood fabric. Any loose fibers seen on the face of the un-weathered products have been weathered away from the rather pitted surface. The color change of the latewood from the light white yellow to the darker brown is especially prominent, and earlywood surfaces have visible translucent cellulose particles.

Allbäck Boiled Organic Linseed Oil

Figure 32. Linseed Oil Sample 3 before (left) and after (right) weathering at 1x magnification (above) and 10 x magnification (below). Photographs by author.

The linseed oil samples exhibited some surface darkening through weathering and earlywood surfaces possessed translucent cellulose fibers, silvering the areas on some samples. The surfaces appear fairly solid and do not appear to have as many micro-checks as the control samples. Roughened areas have some flaking surface material with darkened ends where it appears that cellulose fibers have pulled off in chunks, but the remaining fibers appear mostly stable on the surface.

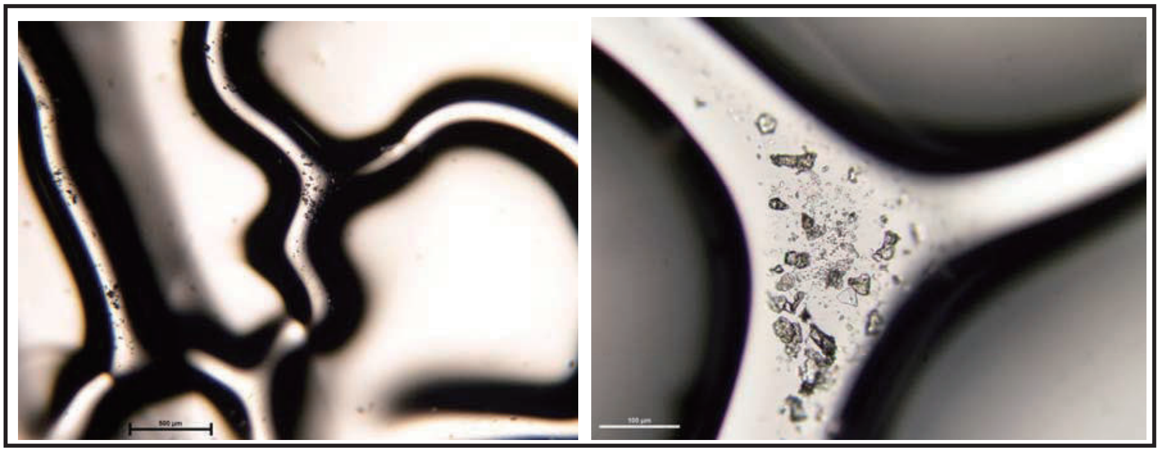


Figure 33. Linseed Oil deposited on a glass slide and inspected at 4x magnification (left) and 20x magnification (right). Photographs by author.

As the linseed oil oxidized, the material pulled inwards and hardened into ridges. The oil is clear upon inspection with the microscope but particles can be seen in the dried oil, likely from contaminants that may have landed on the oil while it was drying.

Paraffin and Mineral Spirits

Figure 34. Paraffin and Mineral Spirits Sample 2 before (left) and after (right) weathering at 1x magnification (above) and 10 x magnification (below). Photographs by author.

The paraffin and mineral spirits coated surfaces behaved much the same as the control. Checks in a range of sizes are spread across the surface and there is a good amount of loose fibers on the surface. Some of these fibers appear to be in process of pulling away from the wood substrate and have been darkened by the UV radiation. The surface of the earlywood is silvered and translucent fibers of cellulose are visible.

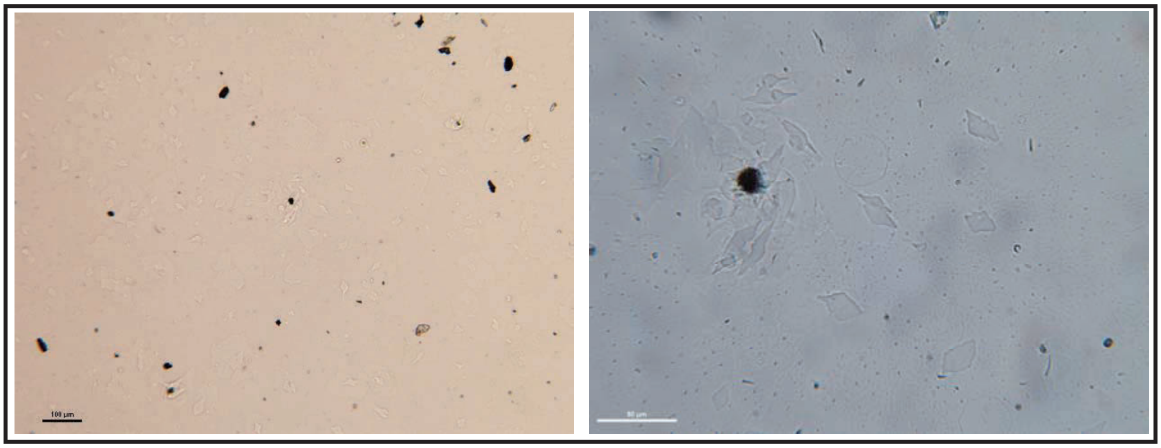


Figure 35. Paraffin and Mineral Spirits deposited on a glass slide and inspected at 10x magnification (left) and 40x magnification (right). Photographs by author.

The coating of paraffin and minerals spirits formed a very thin layer on the slide. Upon close inspection small particles of what appears to be paraffin were deposited on the surface unevenly. This slide was only coated once, but the fairly small amount of paraffin in the recipe may also account for the low concentration.

DEFY Extreme Exterior Clear Wood Stain

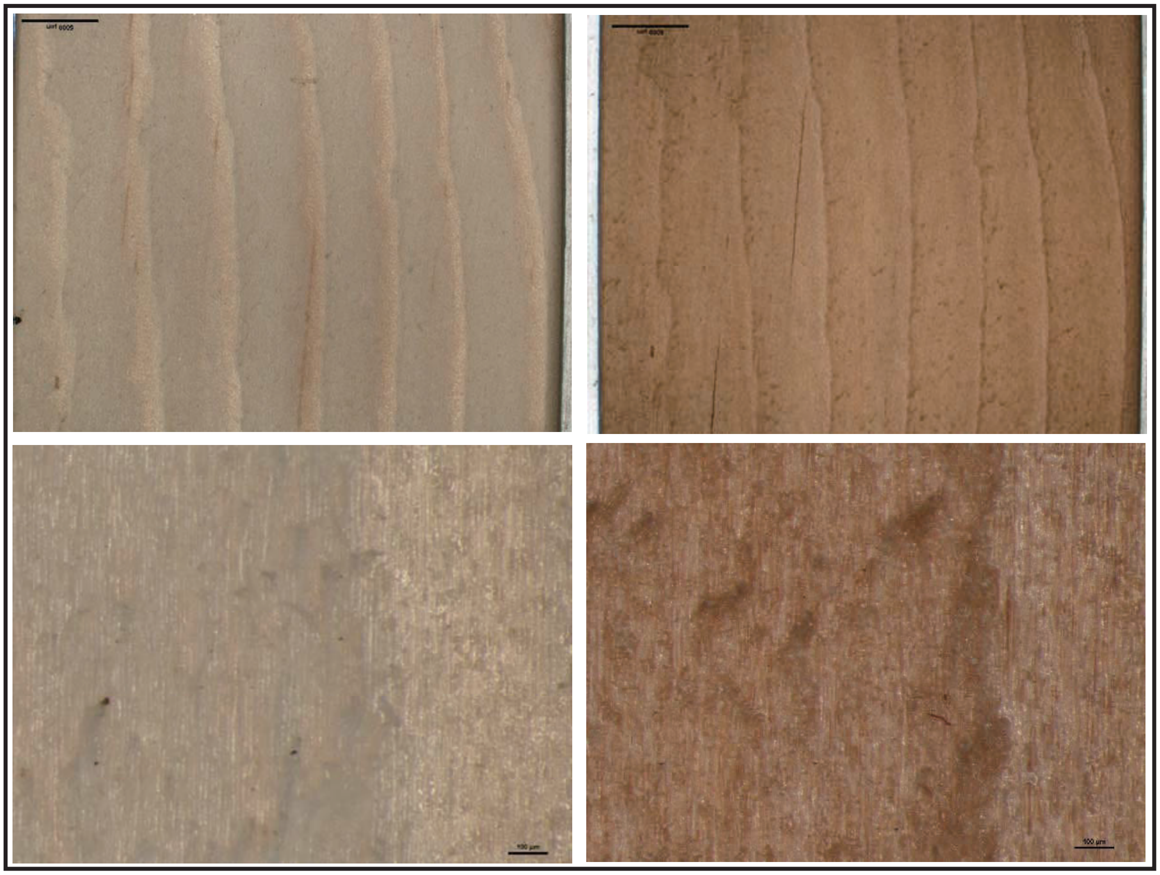


Figure 36. DEFY Extreme Sample 6 before (left) and after (right) weathering at 1x magnification (above) and 10 x magnification (below). Photographs by author.

The surfaces of the DEFY samples darkened significantly with weathering. Latewood grain is visibly raised off of the surface and the earlywood is roughened. Higher magnifications show that the earlywood has a great deal of loose fibers in process of pulling away from the substrate that have darkened. The translucent cellulose particles are fairly prominent in the fabric as well.

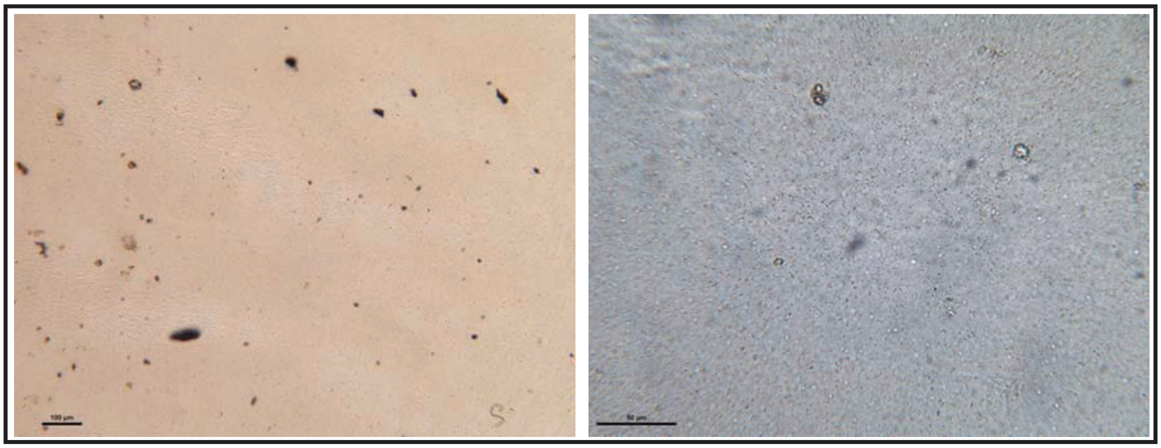


Figure 37. DEFY Extreme deposited on a glass slide and inspected at 10x magnification (left) and 40x magnification (right). Photographs by author.

Upon inspection, the DEFY product deposited a very dense coating of miniscule particles across the slide surface. The particles are well dispersed and appear to have created a fairly even coating across the deposition area.

Armstrong's Wood Stain for Decks (Natural Tone)

Figure 38. Armstrong's Wood Stain Sample 4 before (left) and after (right) weathering at 1x magnification (above) and 10x magnification (below). Photographs by author.

The individual wood fibers are highly visible on the weathered samples of the Armstrong treated samples with some areas where the wood fibers are loose and separating from the surface. Small microchecks dot most of the surfaces, but for the most part not in the same concentrations as in the control samples. Small specks that appear to be inherent in the wood fabric have darkened with weathering and are more visible in the weathered wood fabric.

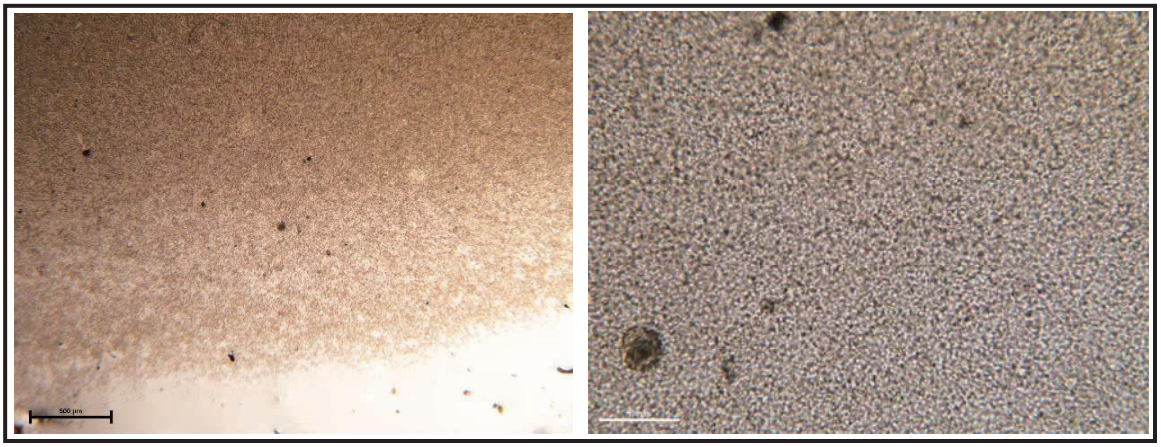


Figure 39. Armstrong's Wood Stain deposited on a glass slide and inspected at 4x magnification (left) and 20x magnification (right). Photographs by author.

The Armstrong Stain deposited dark brown tinted particles across the slide. Upon closer inspection, the particles are well dispersed, highly concentrated, and mostly translucent with a brown sheen. The stain was still not entirely cured upon inspection, and the particles appear to have halos due to their refractive index in the oil base.

TWP 1500 Series Natural Stain (Natural Tone)

Figure 40. TWP 1500 Series Sample 5 before (left) and after (right) weathering at 1x magnification (above) and 10 x magnification (below). Photographs by author.

The weathered wood surfaces of the TWP 1500 Series treatment have fairly prominent cellulose fibers upon inspection, but the translucent quality is not as prominent due to the coloring. The color of the wood is fairly regular across the surface, with little variation between earlywood and latewood. Areas of the surface have partially loose fibers and visible micro-checks. Any imperfections in the wood surface before weathering appear to have been slightly enhanced by the stain coloring, so that the ends of flaking wood fibers are darkened even before weathering.

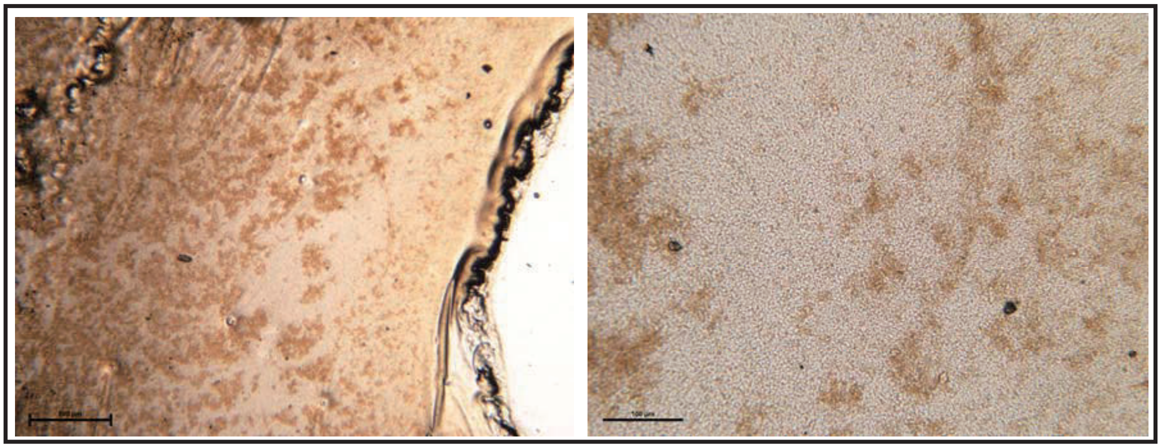


Figure 41. TWP 1500 Series Natural Stain deposited on a glass slide and inspected at 4x magnification (left) and 20x magnification (right). Photographs by author.

The TWP 1500 Series Natural stain also pulled into ridges around the edges of the deposition area upon oxidation. The stain appears to have a mixing of particles, some that are translucent and lightly tinted, and some that carry the color of the stain that clumped together in groups across the sample. These particles are roughly the same size and very well dispersed and thickly deposited on the glass surface.

Flood CWF-UV 5 Penetrating Wood Finish for Fences, Decks, and Siding (Natural Tone (Clear))

Figure 42. Flood CWF-UV 5 Sample 5 before (left) and after (right) weathering at 1x magnification (above) and 10 x magnification (below). Photographs by author.

Some of the surfaces of these sample already appeared rough upon coating with the Flood treatment. The treatment likely coated the wood that was fairly rough from sawing and made the loose fibers even more prominent. The surface is still rough after weathering but with added micro-checks and more prominent cellulose fibers both on the surface and fraying away from the substrate. The earlywood and latewood areas are roughly the same color both before and after weathering and the sample appears to have turned more of an orange tone of brown.

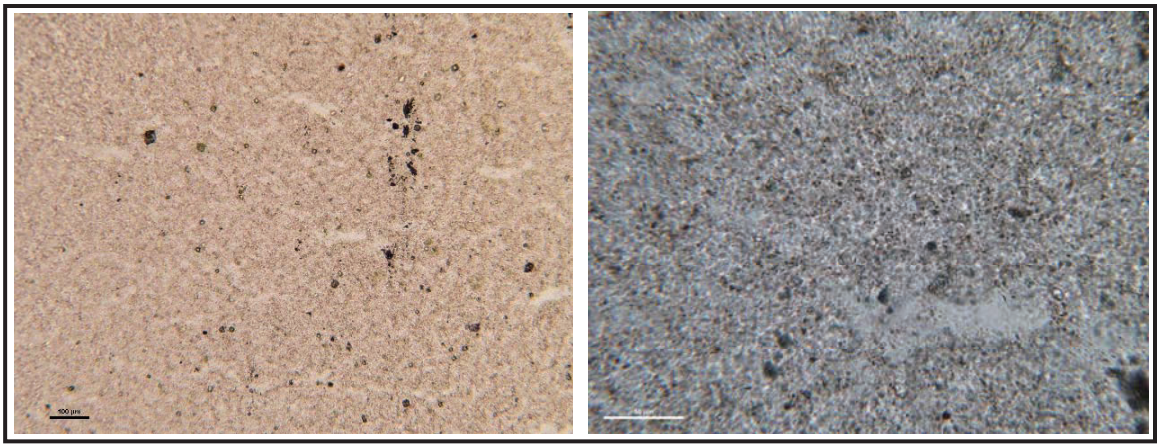


Figure 43. Flood CWF-UV 5 deposited on a glass slide and inspected at 10x magnification (left) and 40x magnification (right). Photographs by author.

The Flood CWF-UV 5 possessed a mixture of particle sizes with fair dispersion. Most of the particles appear to be translucent with the smaller particles lending color to the stain. The particles are fairly evenly distributed and concentrated but certain small areas scattered around the slide surface have very few particles. This is likely due to the stain pulling in certain areas while it coalesced.

Messmer's U.V. Plus Exterior Wood Finish (Natural)

Figure 44. Messmer's UV Plus Sample 1 before (left) and after (right) weathering at 1x magnification (above) and 10 x magnification (below). Photographs by author.

Similarly to most of the colored treatments, the Messmer's product, upon closer inspection, appeared to highlight the already rough quality of the wood before weathering. The latewood grain is raised after weathering and many of the surfaces are fairly rough but with less instances of singular or small groups of cellulose fibers pulling off of the surface. Instead, for the most part, the roughened cellulose fibers appear attached, perhaps by the product. The cellulose fibers are fairly prominent on the surface of the samples and the weathered wood does not show a great difference in color between the earlywood and latewood due to the pigmentation.

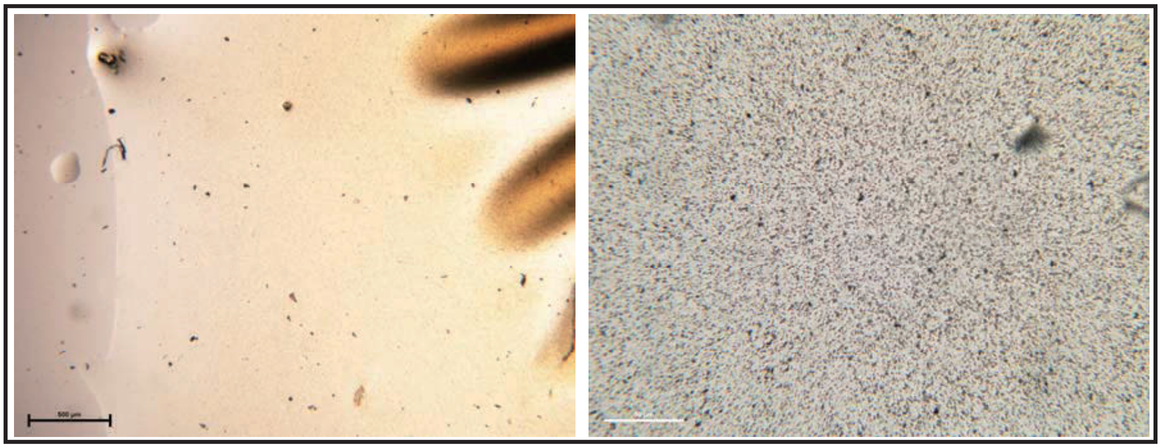


Figure 45. Messmer's UV Plus deposited on a glass slide and inspected at 4x magnification (left) and 40x magnification (right). Photographs by author.

The Messmer's product behaved much the same as the linseed oil upon drying, it formed ridges of stain on the glass surface as it oxidized. The particles in the stain are very small with very good dispersion and fairly high concentration. Some of the particles appear to be translucent, but for the most part they appear dark brown.

4.1.2 Weight Change

Weight changes from pre- to post-weathered samples can serve as a good indicator of physical degradation of the wood surface as well as the penetrating treatments. Each full length sample, containing two samples each (1-2, 3-4, 5-6), was weighed after treatment before weathering and after weathering; the samples were measured for moisture content at both times of measurement to ensure that each weight was a good representation of the wood fabric rather than for excess water.[1] Moisture content was measured using a Wagner MMC 210 Moisture Meter and the samples were weighed on an Adventurer OHaus Analytical Balance.[2]

There was a range in the weights of each sample due to the variability of the wood fabric, but weight change measurements and percentage values in table 5 reflect relatable degradation of fabric and treatments between the products. Some products had a greater range of percent weight loss between the three long samples, while others varied very little. Though there was an effort to regularize the samples as much as possible, this irregularity could be due to conditions in certain samples such as ratio of earlywood to latewood, how much treatment was accepted into the wood fabric, any abnormalities in the wood fabric, moisture content, etc.

The control samples lost between approximately 1.5-2.5% of their weight in the weathering process, a fairly large range when compared to the other samples, though a smaller amount of fabric lost than any other samples. This discrepancy is likely because the control samples lost just wood material, rather than both wood and product loss like with the treated samples. Armstrong's Wood stain lost the smallest percentage of wood and product of the treated samples, ranging from 1.4-2.45%, while TWP 1500 Series appears to have lost the greatest percentage of product on average, ranging from 2.4-3.04%. Most of the treated samples appear to have lost around 2.5% of their weight, with some samples such as those treated with DEFY losing slightly less than this figure and some losing slightly more. In any case, there does not appear to be a huge discrepancy between many of the products in the amount of wood fabric and product they lost during the weathering process.

[1] It is for this reason that weight measurements taken throughout the experiment at every 100 hours were not used. At each 100 hour mark, the samples were at different points in the cycles so their weights fluctuated greatly and did not volunteer much insight into material loss.

[2] The precision of the Ohaus G160 balance is +/- 0.0001g (STD DEV) and the linearity is +/- 0.0003g according to the instruction manual.

	Sample	Weight (Post-Treatment, Pre-Weathering)	Moisture Content (Pre-Weathering)	Weight (Post-Weathering)	Moisture Content (Post-Weathering)	Mass of Treatment Absorbed	Weight Change	Percent (%) Weight Loss
Control								
	CON-1 & CON-2	72.77	8.9 / 8.4	71.71	8.6 / 8.7	n/a	**1.06**	**1.46**
	CON-3 & CON-4	70.27	8.0 / 7.6	69.14	7.4 / 7.6	n/a	**1.13**	**1.61**
	CON-5 & CON-6	74.46	8.9 / 8.9	72.49	7.3 / 7.5	n/a	**1.97**	**2.65**
Linseed Oil								
	LIN-1 & LIN-2	74.93	8.5 / 8.3	73.30	8.3 / 8.3	1.84	**1.63**	**2.18**
	LIN-3 & LIN-4	64.45	7.2 / 7.8	62.65	7.1 / 7.4	2.17	**1.80**	**2.79**
	LIN-5 & LIN-6	77.71	9.5 / 9.5	75.67	9.1 / 9.5	1.15	**2.04**	**2.63**
Paraffin and Mineral Spirits								
	PAR-1 & PAR-2	77.18	8.2 / 8.7	75.55	9.2 / 9.8	0.77	**1.63**	**2.11**
	PAR-3 & PAR-4	65.01	7.5 / 7.1	63.35	6.8 / 7.1	1.19	**1.66**	**2.55**
	PAR-5 & PAR-6	76.86	9.8 / 9.6	74.67	9.2 / 8.6	0.19	**2.19**	**2.85**
DEFY Extreme								
	DEF-1 & DEF-2	78.22	7.6 / 8.1	76.48	8.2 / 8.6	1.35	**1.74**	**2.22**
	DEF-3 & DEF-4	62.15	7.3 / 6.9	60.77	7.9 / 7.7	1.58	**1.38**	**2.22**
	DEF-5 & DEF-6	67.57	7.9 / 8.5	65.65	8.1 / 8.2	0.82	**1.92**	**2.84**
Armstrong's Wood Stain								
	ARM-1 & ARM-2	76.02	8.9 / 9.5	74.16	8.7 / 8.9	1.72	**1.86**	**2.45**
	ARM-3 & ARM-4	75.51	8.0 / 7.8	73.95	8.4 / 8.2	2.23	**1.56**	**2.07**
	ARM-5 & ARM-6	81.18	9.1 / 8.7	79.78	9.8 / 9.8	2.05	**1.14**	**1.40**
TWP 1500 Natural								
	TWP-1 & TWP-2	59.27	6.8 / 6.6	57.47	6.2 / 6.6	1.26	**1.80**	**3.04**
	TWP-3 & TWP-4	73.87	8.6 / 9.0	72.08	8.7 / 8.6	0.86	**1.79**	**2.42**
	TWP-5 & TWP-6	74.59	7.9 / 8.4	72.80	7.9 / 8.1	0.76	**1.79**	**2.40**
Flood CWF UV-5								
	FLO-1 & FLO-2	77.21	8.7 / 9.2	75.58	8.7 / 9.3	1.10	**1.63**	**2.11**
	FLO-3 & FLO-4	73.72	9.7 / 9.8	71.60	8.5 / 9.0	0.88	**2.12**	**2.88**
	FLO-5 & FLO-6	79.27	9.8 / 9.8	77.38	9.2 / 9.8	0.61	**1.89**	**2.38**
Messmer's UV Plus								
	MES-1 & MES-2	69.56	7.9 / 8.4	67.82	6.8 / 7.1	0.88	**1.74**	**2.50**
	MES-3 & MES-4	67.88	7.6 / 7.3	66.24	7.2 / 7.4	1.14	**1.64**	**2.42**
	MES-5 & MES-6	69.10	7.3 / 7.3	67.32	6.6 / 7.1	1.22	**1.78**	**2.58**
Curved								
	LIN-CURV & FLO-CURV	90.43	6.3 / 7.1	90.30	6.3 / 6.1	1.49	**0.13**	**0.14**
	PAR-CURV & AND DEF-CURV	96.70	5.2 / 6.3	96.63	5.7 / 5.5	0.12	**0.07**	**0.07**
	ARM-CURV & TWP-CURV	91.39	8.9 / 8.9	90.46	8.1 / 6.8	0.04	**0.93**	**1.02**
	CON-CURV & MES-CURV	109.54	6.0 / 6.2	109.29	6.0 / 6.3	0.30	**0.25**	**0.23**

Table 5. Weight changes from pre-weathering to post-weathering showing weight gained during treatment, amount of weight lost during weathering, and the percentage of weight lost.

4.1.2.1 T-test

The paired (dependent) t-test was used to compare the mean weight of each sample cohort by comparing the initial weights before and after weathering. The values were calculated using a data analysis plug-in on Microsoft Excel[3] based off of the equation mentioned previously in Section 3.5. Likely due to the variance in wood composition even within the same set of logs from which the samples were cut, only a few sample cohorts passed the t-test. Where the t critical values exceeded those of t stat values (the control, DEFY, and curved samples) at the 95% confidence interval at 5 degrees of freedom, the null hypothesis was accepted so there was not difference in the mean between the sample weights before and after weathering. However, in those samples where the opposite was true (the linseed oil, paraffin and mineral spirits, Armstrong's, TWP 1500 series, Flood, and Messmer's) the null hypothesis was rejected and there was a difference in the mean between the sample weights before and after weathering.

[3] Calculations can be found in Appendix G.

Sample		Weight Change after Weathering
Control	t Stat	3.69047619
	t Critical	6.313751515
	pass / fail?:	**pass**
Linseed Oil	t Stat	16
	t Critical	6.313751515
	pass / fail?:	**fail**
Paraffin and Mineral Spirits	t Stat	7.264150943
	t Critical	6.313751515
	pass / fail?:	**fail**
DEFY Extreme (Clear)	t Stat	6.111111111
	t Critical	6.313751515
	pass / fail?:	**pass**
Armstrong (Natural)	t Stat	18.5
	t Critical	6.313751515
	pass / fail?:	**fail**
TWP 1500 (Natural)	t Stat	3.515892051
	t Critical	2.91998558
	pass / fail?:	**fail**
Flood CWF UV-5 (Natural)	t Stat	17.43478261
	t Critical	6.313751515
	pass / fail?:	**fail**
Messmer's UV Plus (Natural)	t Stat	24.42857143
	t Critical	6.313751515
	pass / fail?:	**fail**
Curved Samples	t Stat	1.591098456
	t Critical	2.91998558
	pass / fail?:	**pass**

Table 6. T-test values for the weight change before and after weathering.

4.1.3 Color Change

Absorption of ultraviolet radiation and the subsequent degradation of lignin in the wood substrate is the primary cause of color change in the weathering of wood. The wood gets darker with the accumulation of the lignin degradation products, and, as these product wash away, becomes lighter and more silvered due to the accumulation of cellulose fibers at the surface.

Photographs taken of the samples before, during, after weathering are helpful for observing the physical change that the samples underwent.[4] However, even with color and white balance correction using an X-rite Colorchecker Passport and Adobe Photoshop, photographs cannot be used as an accurate display of color change. Light sources as well as the moisture content of the wood varied between the photographs, for the samples were taken out of the machine at the one hundred hour marks no matter what time of day or in which cycle they were being exposed. Thus, many times samples were photographed at night when daylight was not available and a flash could not be used because it caused too great of a reflection on the metal portions of the specimen brackets to see the samples properly.[5] In addition to poor lighting, when the samples came out of a condensation cycle, they were often darker due to high moisture contents.[6]

Due to these discrepancies as well as for quantitative measurements of color change, a Konica Minolta Spectrophotometer CM-2500d was used to observe changes in the wood fabric and coatings in three different scenarios: from before treatment to after treatment, before weathering to after weathering, and comparison of the weathered control sample to the weathered coated samples.[7] These three scenarios were chosen to better understand the aesthetic changes that occur when a sample is coated with a certain product, how that product weathers and whether it is protecting the wood, and how that product compares to the

---

[4] Refer to Appendix F for a full set of photographs of the samples as they underwent the weathering process.
[5] In future testing a better indirect lighting system should be developed to alleviate this problem.
[6] If the samples are to be monitored throughout the process of weathering in future tests, a strategy should be developed to record their progress in different increments than strictly every 100 hours. Instead they could be monitored at the end of every 25 ultraviolet exposure cycles (roughly every 100 hours) so that moisture contents would be generally the same and measurements more contiguous.
[7] These measurements were taken according to ASTM D2244 − 14 - Color Tolerances and Differences from Instrumentally Measured Color Coordinates.

weathering of the uncoated wood substrate.[8] As previously mentioned in the methodology, the CIE 1976 L*a*b* system was used for evaluation using SpectraMagic NIX software for processing changes (L*Δa*Δb* and ΔE* overall) in each scenario. A target sample was first taken using the spectrophotometer to obtain the values for the standard to which the sample is being compared and then the actual sample was measured for comparison. The software then generated color values as well as calculated the overall difference (ΔE) and the shifts in the axes L*, a*, and b* for comparison purposes.[9]

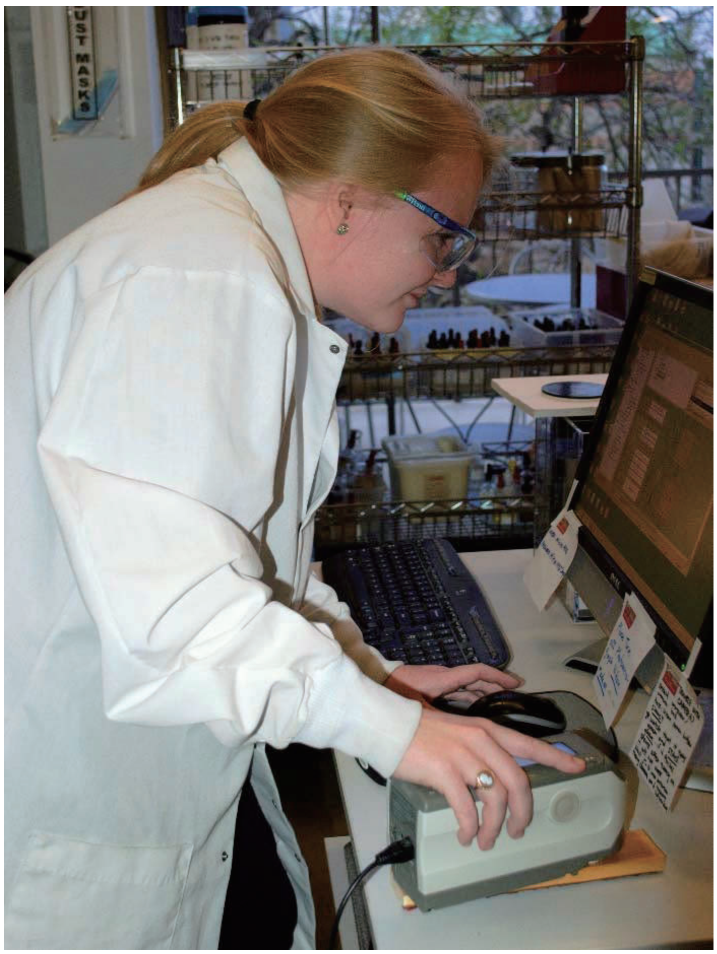


Figure 46. Taking color measurements using the Konica Minolta Spectrophotometer in the Architectural Conservation Laboratory. Photograph by the author.

[8] Color measurements were taken throughout the weathering at 100 hour increments; however, because of the varying moisture contents mentioned in the text, these values were deemed unusable because they were dispersed across the color map and not conducive to understanding the decay process.
[9] All graphs and values generated can be found in Appendix C.

Sample	Before and After Treatment (ΔE) (Average)	Before and After Weathering (ΔE) (Average)	Weathered Sample to Weathered Control (ΔE) (Average)
Control	n/a	24.69	n/a
Linseed	17.23	29.25	13.99
Paraffin	2.59	25.75	5.69
Defy	4.12	30.04	8.30
Armstrong	21.27	20.48	8.92
TWP	26.89	15.43	14.22
Flood	22.88	26.30	22.64
Messmer's	29.55	20.05	20.75

Table 7. Average values of color change for each scenario. For the full set of values for each cohort refer to Appendix C.

In order to best understand the average color change values expressed above and in more detail in Appendix C, each color scenario is considered below:

Before and After Treatment

Color measurements taken before and after treatment lend insight into how much a treatment affects the initial aesthetic quality of the wood surface. A larger ΔE indicates a greater aesthetic shift initially. Though the smallest amount of change is usually ideal in conservation treatments, for aforementioned reasons larger shifts towards the actual color of the extant weathered wood can allow new replacements to better fit into the fabric of the building without disturbing the aesthetics. This thought is especially applicable in the second scenario in how the treated wood weathers over time.[10]

[10] Ideally, in future testing historic weathered and treated wood from the area would be available for comparison in color values to get a more accurate idea of which treatment might be the most appropriate for each structure.

The changes observed had a large range of about 27 units between those products having the least impact on the un-weathered wood, paraffin and mineral spirits as well as DEFY by far having the smallest effect, to those having the greatest impact before weathering, Messmer's showed the greatest change. The four lightly pigmented products of course showed the greatest difference, all in the range of the 20's, and linseed oil displayed only a slightly lower shift from the original fabric color.

Before and After Weathering

The surfaces of weathered samples were compared to the small sections that had been cut off of their ends before weathering commenced but after the pieces had been treated. This difference measurement was taken in an effort to understand the aesthetic change that each treated wood sample underwent during weathering. As mentioned above, this aesthetic change is important in terms of long-term effects of the conservation treatment when used in comparison to the color of historic fabric originally, the color it changes to upon treatment with the same product, and how the treated historic sample changes with weathering.[11]

The range of average ΔE was smaller for this portion of the experiment, less than 15 units. DEFY underwent the largest amount of change likely because the treatment had very little aesthetic effect on the new sample surface. The color shift was greater than in that of both the control and paraffin and mineral spirits, which started as roughly the same values, though these initially light-colored samples did darken quite a bit from their original tone. Linseed oil treatment also had a similarly large shift of 29.25. TWP 1500 Series showed the smallest change

[11] All of these factors will be evaluated in the coming summer when natural weathering is conducted on site and historic material is available for testing purposes.

during weathering, only 15.43, and the other color-pigmented oil products, Armstrong's and Messmer's, also had fairly low shifts around 20 because of their already dark surfaces.

Weathered Sample to Weathered Control

In an effort to best understand how a treated sample might compare aesthetically to a piece of weathered historic pine that has not been treated, or from which previous treatments have weathered out, treated weathered samples were compared to the weathered control sample. These comparisons can lead to better-educated decisions about what treatments may be an aesthetic fit for a site. Without the actual color measurements for material on site, however, the control can only serve as a proxy. The wood found at various log structures in Grand Teton National Park is usually darker than that seen on the weathered control, but it serves its purpose for comparison.[12]

The values ranged from 5.69, paraffin and mineral spirits, to 22.64, Flood; DEFY and Armstrong's were also within 10 units of the weathered control, and linseed oil and TWP were within 15 units. Messmer's also had a greater difference from the control with a ΔE of 20.75.

4.1.4 FTIR

Fourier Transform Infrared Spectroscopy sampling by transmission was conducted at the labs of the Philadelphia Museum of Art using a Nexus 670 FTIR and OMNIC Processing. The samples were inspected in the middle region of the spectrum, ranging from 500 – 4000 wavenumbers. Due to limits on testing time, only one sample of each treatment could be tested, so sample 1 was used for the whole range of treatments for continuity. A very small amount of

[12] Interaction with logs on historic sites in the Park as well as photographs and historical information about the previous oil treatments for the logs on sites such as the Bar BC informs the knowledge that the wood on these structures is darker than that seen in this lab experiment.

surface material was carefully removed using a clean scalpel and deposited in a diamond cell where it was further pressed into the cell with a metal roller.[13] The cell was then placed under the microscope and background measurements were taken 200 times before material analysis to ensure that the diamond cell did not interfere with the bands of the wood and the products.

Figure 47. The FTIR arrangement in the Philadelphia Museum of Art. Photograph by the author.

A video screen was used to center the infrared beam on the edge of sample material, for the sample cannot be too thick for an accurate reading. Once an acceptable sample was found with initial readings, the spectra was generated 200 times to form the resulting graphs.[14] The spectra for un-weathered and weathered lodgepole pine was first inspected in order to confirm peaks listed in previous papers that used infrared spectroscopy to monitor wood and paper

[13] Many sampling techniques suggest powdering solid samples and mixing them with an IR transparent material such as Potassium Bromide (KBr) to compress into pellets for readings. This method usually provides excellent results and can be suggested for future testing, but it is time-consuming and was not used for these readings.
[14] All graphs can be found in Appendix D.

degradation (Lionetto et al., 2012; Proniewicz et al., 2002; Schmalzl and Evans, 2003). Each of these papers listed a variety of peaks for wood components, but all listed the small peak at about 1508 wavenumbers (cm^{-1}) as an indicator for lignin that can be monitored to detect wood fabric degradation. Spectra of the un-weathered surface and several areas of the weathered surfaces confirmed the presence of the peak from the fabric before weathering and its subsequent absence in the three sampling locations of weathered fabric.

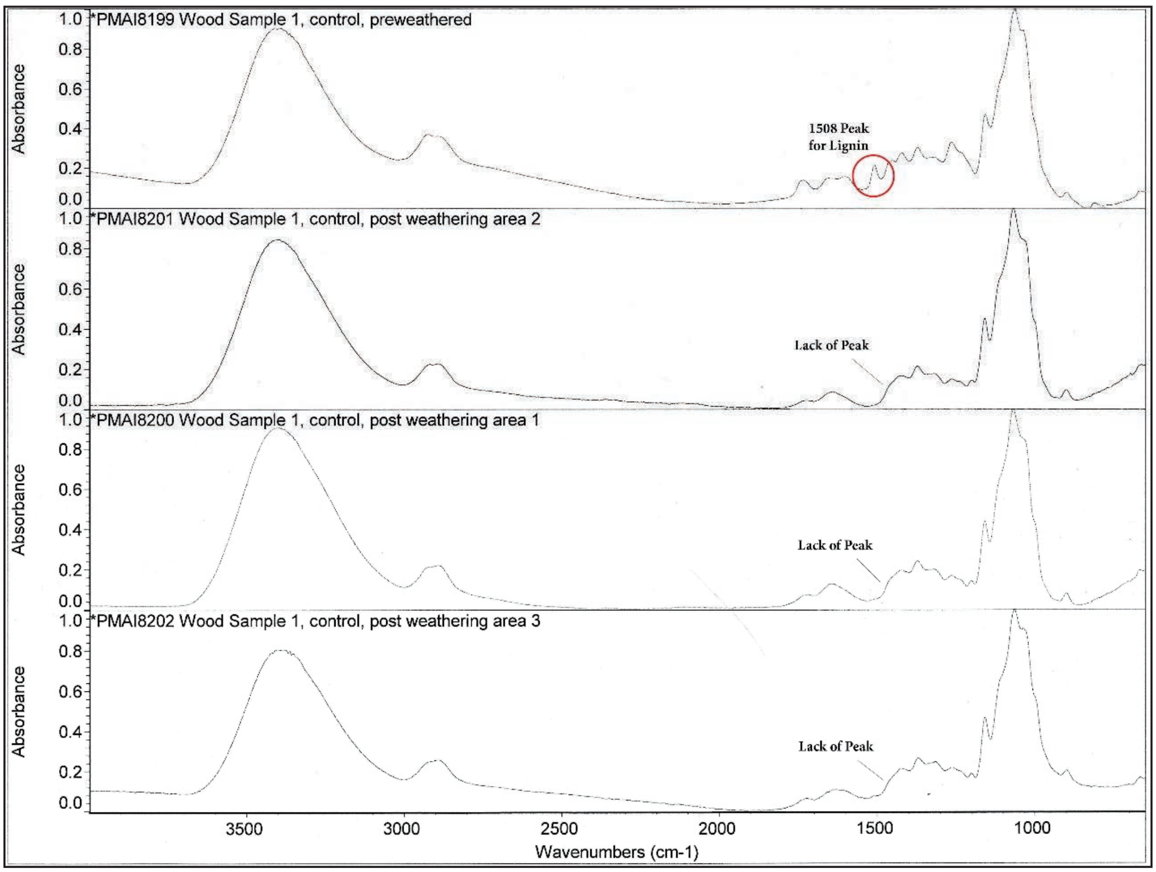


Figure 48. Spectra for Control Sample 1 before and after weathering confirmed that the peak for lignin at 1508 wavenumbers was a good indicator for weathering and subsequent loss of lignin. Spectra generated at the Philadelphia Museum of Art.

Due to a lack of knowledge about what exactly was in the proprietary treatments, the analysis of the coated samples is more of a qualitative study to determine if each product prevented lignin loss and whether it still remained in the surface of the sample or had weathered away (addressed in a later section of this chapter). This analysis does not attempt to determine the concentrations of each component in the wood and products for there were no standards for evaluation of comparative peak intensities.

Further testing on the control samples reinforced the typical bands and intensities of lodgepole pine before and after UV degradation for analysis of the treated samples. The spectra for two different areas of the weathered sample treated with linseed oil shows that lignin has entirely disappeared from the surface of the wood. Both areas on the weathered paraffin and mineral spirits sample displayed the same, though with possibly a small peak at 1508 on area two, perhaps indicating a small amount of lignin in the fabric.

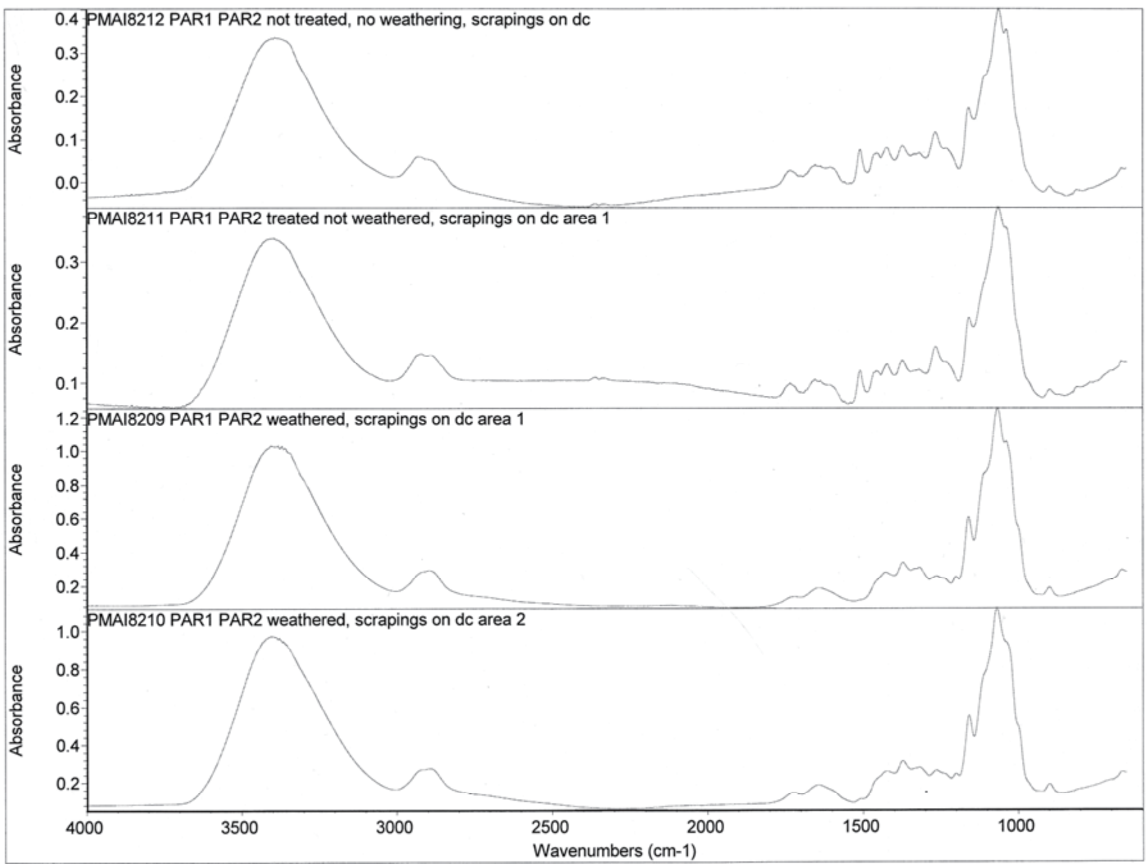


Figure 49. Spectra of paraffin and mineral spirit coated samples before and after weathering. Spectra generated at the Philadelphia Museum of Art.

Some component found in the composition of DEFY Extreme, likely an acrylic polymer, may have interfered with the spectrum at the 1508 wavenumber so that the band for lignin, if it is present, is obscured in the weathered sample. Therefore, the small peak at 1508 may indicate the presence of lignin or may be a part of this polymer. This polymer may be a degradation component of something in the coating, for there is only interference in the weathered sample and not the treated and pre-weathered sample.

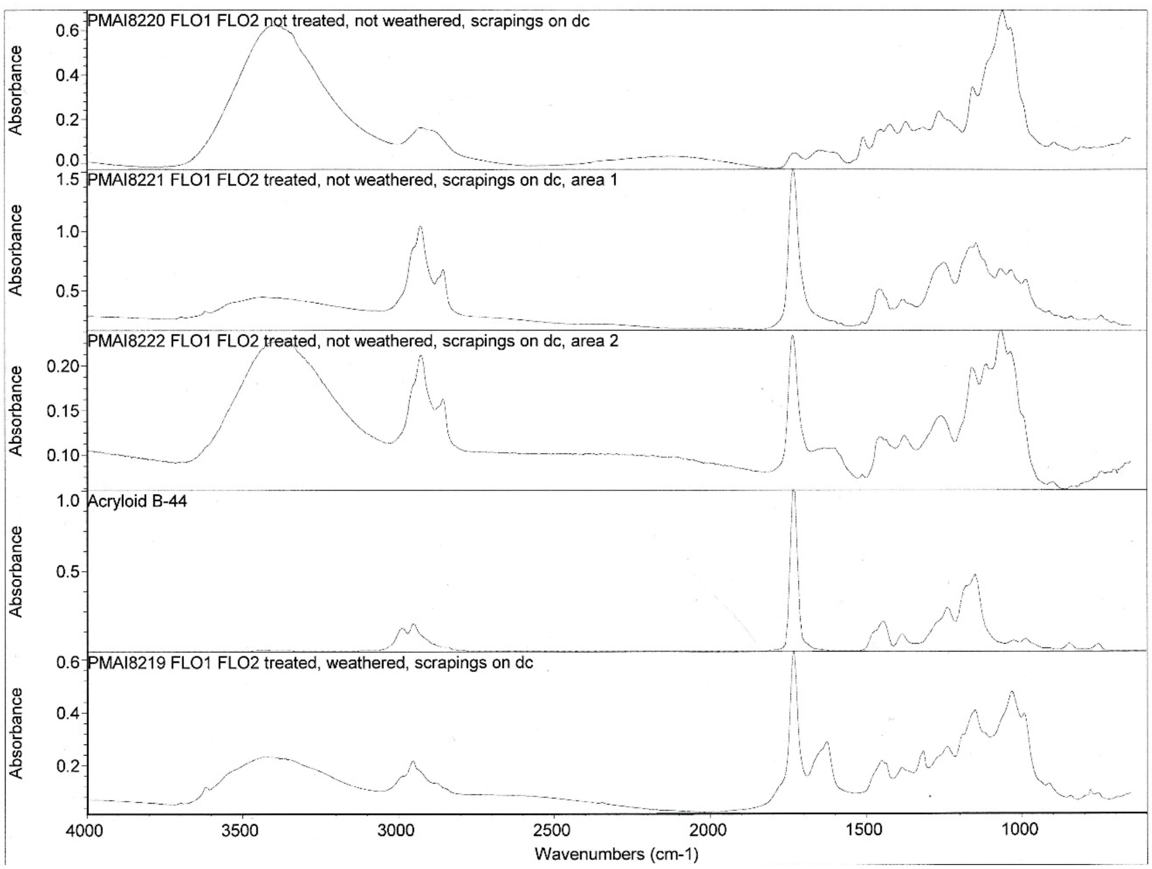
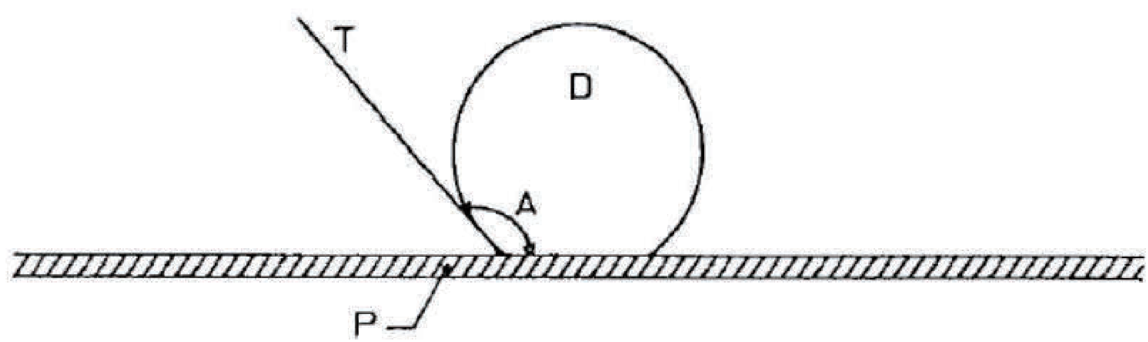


Figure 50. Spectra of Flood CWF-UV 5 showing before and after weathering as well as an acryloid standard for comparison to the coating. Spectra generated at the Philadelphia Museum of Art.

The other acrylic-based product, Flood, also shows interference at the target wavenumber from an acrylic coating component. Small peaks on the un-weathered spectra of sample areas one and two may indicate the presence of lignin before weathering, but the weathered sample does not have this small peak at all. The spectra for Armstrong's Wood Stain shows a definite peak loss at 1508 wavenumbers, though a small bump on each may indicate some lignin material; the Messmer's product is much the same, with a small peak possibly indicating a very small amount of lignin. The spectra for TWP shows a distinct lack at the 1508 lignin peak. Further analysis using FTIR can be found in section 4.3 of this chapter on product retention.

4.2 Water Repellence (Hydrophobicity)

The purpose of the contact angle test in this experiment, outlined in ASTM D7334-08 Standard Practice for Surface Wettability of Coatings, Substrates and Pigments by Advancing Contact Angle Measurement, is to determine the hydrophobicity of the coatings on the wood surface and how accelerated weathering may have affected the water resistance of the coatings.



A = contact angle
D = drop of liquid
P = specimen
T = tangent at specimen surface

FIG. 1 Measuring Angle of Contact

Figure 51. Diagram showing how contact angles are measured using liquid droplets on flat surfaces. Image from ASTM D7334 – 08 - Standard Practice for Surface Wettability of Coatings, Substrates and Pigments by Advancing Contact Angle Measurement.

The experiment deals with measurement of the angle of contact when a drop of liquid is applied to a coated surface. This angle is the interior angle that a drop makes between the substrate and a tangent drawn at the intersection between the drop and the substrate. These angles are governed by surface tension, an effect that arises from unbalanced molecular cohesive forces at a surface that cause the surface to contract and behave like a membrane, but cannot be used to measure surface tension directly (ASTM D7334 – 08). By measuring the advancing contact angle, the angle immediately after the drop is deposited on the surface, the hydrophobicity of the coating and wood surface can be determined; for water, an angle less than 45˚ indicates a hydrophilic surface, greater than 90˚ indicates a hydrophobic surface, and anywhere between 45-90˚is intermediate.

Different liquids can be used for contact angle measurement, but the fluid used in this experiment was deionized water. A transfer pipette was used to deposit drops of water, termed sessile drops, onto the top (tangential) surface of samples and a camera set up with a mounted concave lens was used to record the drop immediately after it was placed on the surface. These photos were then processed using the plug-in Contact Angle in the open-source software ImageJ to calculate contact angles. Manual Point Procedure was used to calculate the angles: points of intersection of the water with the surface on either side of the drop were selected followed by at least three more points along the edge of the curved drop. The plugin then generated a best-fit ellipse and calculated the angles of contact. This experiment was performed on each sample, pre- and post- weathering surfaces, as well as on a glass slide for comparison.

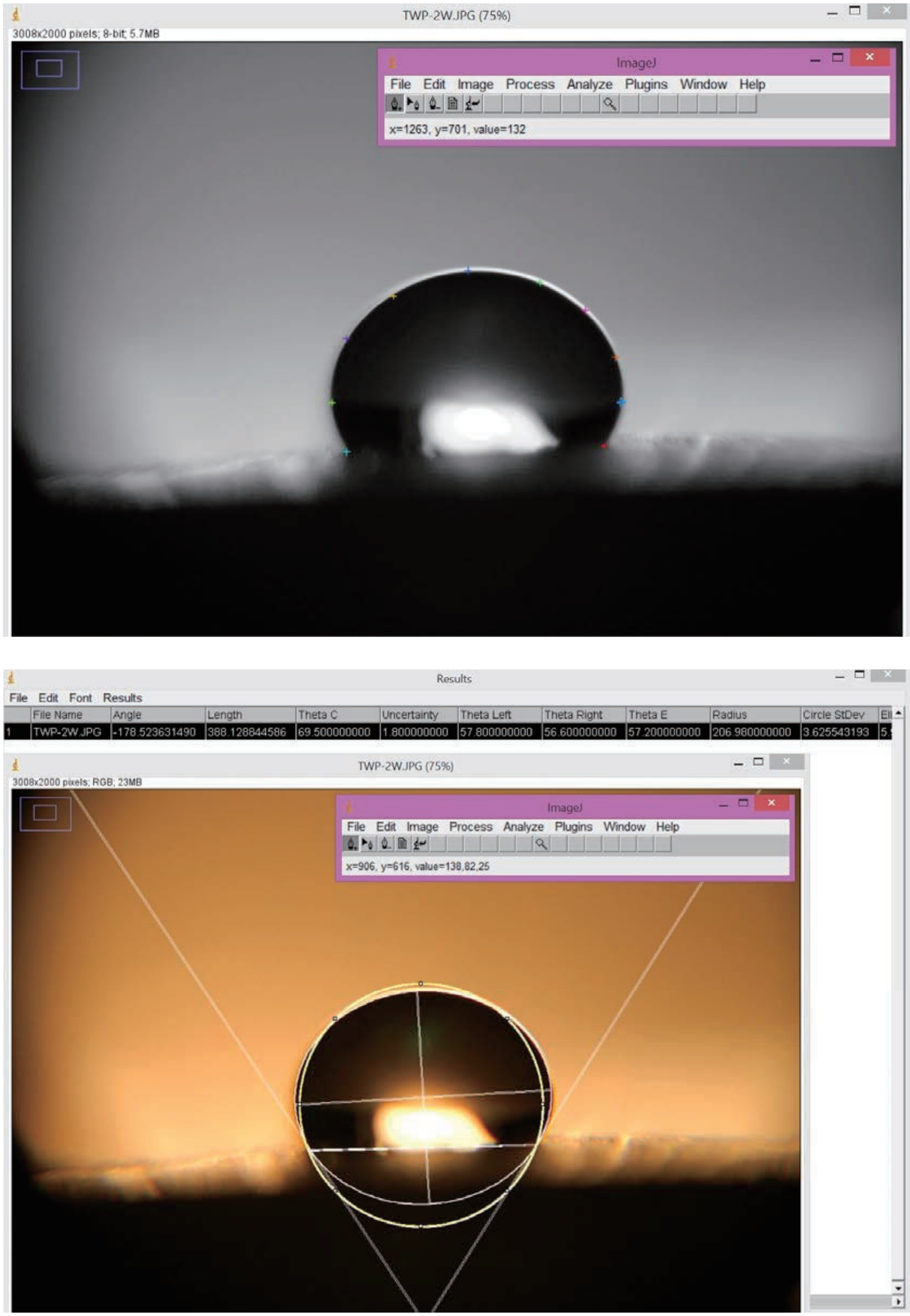


Figure 52. Droplet processing using the Contact Angle plug-in on ImageJ. Points are selected around the edges of the drop to create the most accurate fit (top) and the software subsequently processes the best-fit ellipse or circle and calculates the angle of interaction with the axis of the surface to generate the contact angles on both sides of the droplet. Photographs by author.

A transfer pipette was used to drop water onto the sample surfaces. The dropper was held perpendicular to the surface and squeezed gently so that a solitary drop of water fell a short distance to the surface. The placement of the pipette tip close to the surface was an effort to diminish any risk of kinetic energy dispersing the drop in its fall. The growing pendant drop from the pipette touched the surface and detached before falling of its own free weight. The consistency of this method was first measured using an Adventurer OHaus Analytical Balance. Water droplets were dropped onto the balance ten times each weighing 0.04 g, 0.04 g, 0.04 g, 0.04 g, 0.04 g, 0.04 g, 0.04 g, 0.04 g, 0.04 g, and 0.04 g.[15] Thus, the pipette method was very consistent in volume and was considered reliable.

The set up for the experiment included a horizontal stage on which the sample was placed. In order to focus the camera lens on the water droplet, a mounted plano-convex lens with a focal length of 50 mm was placed between the camera and the sample area, held in place with another clamp and stand.[16]

[15] 0.4 grams correlates to 0.4 milliliters, so for each contact angle taken, 0.4 mL was deposited on the wood surface.

[16] An N-BK7 glass lens with an anti-reflection coating for the 350-700 nm range and Ø1" optics. Model LA-=1131-A-ML from Thorlabs.

Figure 53. The N-BK7 convex lens used to the focus the camera lens on the drop for photograph. Photograph by author.

The lens was located one inch from the sample stage and two inches from the camera lens, focusing the image on the droplet. A light source, was placed behind the sample stage facing the camera in order the illuminate the contact region from behind and allow greater contrast in the image for more accurate measurement (Figure 54). The water drop was dropped ¼” deep in the sample plane away from the lens and towards the light. Photographs were taken no more than ten seconds after the drop had been deposited in order to gain the most accurate reading of the contact angle. A full list of photographs can be found in Appendix E. The photographs were not further edited in an imaging software except to convert them to grayscale for measurement.

Figure 54. The set up for photographing the water droplets. The camera is focused through the convex lens on the droplet of water deposited on the wood sample surface while a light source provides backlighting for a sharper image. Photograph by author.

A variety of factors that are very pertinent to the nature of the samples in this experiment have a possibility of interfering with results. Curved as well as rough surfaces where the drop is not quite level or may sink into the wood affected the angles and their measurement in this experiment. This is exemplified in the chart of angle values when the angle on the left side is quite different from that on the right.[17] Additionally, in using water as the test liquid, low humidity (less than 50% relative humidity) can cause the water droplet angle to change rapidly. The lab environment remains around 36% RH and the moisture content of the wood samples at the time of the experiment averaged around 8%, so this had to be taken into account in conclusions about results. Additionally, the curved samples were not tested using this method because they do not have flat surfaces that could be measured. Finally, a slightly larger drop size may have proven easier to measure for angles.

The set of angles found for each sample pre- and post-weathering are listed in table 8, and the observations recorded during experimentation for each treatment are recorded below:

[17] Weathered paraffin and mineral spirts samples 4 and 5 have extreme angle differences due to the very rough surface and the cupping of the sample.

	Sample	Pre-Weathering Left Angle (˚)	Pre-Weathering Right Angle (˚)	Post-Weathering Left Angle (˚)	Post-Weathering Right Angle (˚)
Control					
	CON-1	97.9	87.6	135.9	132.1
	CON-2	95.9	88.4	127.5	134.7
	CON-3	94.5	90.4	149	140.2
	CON-4	107.4	104.8	141.9	151.1
	CON-5	80.3	80.3	109.3	67.9
	CON-6	96.2	91.1	100.7	96.8
Linseed Oil					
	LIN-1	84.9	84.9	85	82.1
	LIN-2	81.3	78.9	71.6	78.5
	LIN-3	85.6	86.7	83.5	85.2
	LIN-4	77.7	73.8	66.9	65.9
	LIN-5	71.9	68.7	72.4	72.1
	LIN-6	86.4	81.9	70.1	78.7
Paraffin and Mineral Spirits					
	PAR-1	77.9	80.4	n/a	n/a
	PAR-2	74.4	74.2	n/a	n/a
	PAR-3	93.9	88	n/a	n/a
	PAR-4	67.7	64.7	146.7	70.7
	PAR-5	84.8	88.7	76.9	113
	PAR-6	75.2	76.9	131.4	132.5
DEFY Extreme (Clear)					
	DEF-1	107.8	99.9	86.2	82.1
	DEF-2	93.1	97.6	79.9	80.5
	DEF-3	74.9	72.8	76.8	78.4
	DEF-4	57	58.8	81.2	86.6
	DEF-5	64.2	61.8	88.4	86.4
	DEF-6	61.4	61.2	77.7	81.3
Armstrong (Natural)					
	ARM-1	63	66.4	76.6	73.6
	ARM-2	67.6	65.6	82.2	88.3
	ARM-3	74.2	72	68.6	69.5
	ARM-4	64.7	64.5	69.3	69.5
	ARM-5	75.7	74.8	84.2	79.6
	ARM-6	67.8	69.9	78.9	74.8
TWP 1500 (Natural)					
	TWP-1	67.4	69	71.2	73.3
	TWP-2	59.9	59.1	57.8	56.6
	TWP-3	68.6	69.2	60.1	63.1
	TWP-4	47.7	49.1	61.4	67.5
	TWP-5	67.4	69.5	67.1	72.2
	TWP-6	65.5	65.5	65.1	65.6
Flood CWF UV-5 (Natural)					
	FLO-1	74.2	74.4	92.4	109.9
	FLO-2	79.7	80.6	101.3	100.5
	FLO-3	78.9	77.5	106.4	107.5
	FLO-4	96.4	96.5	94.4	97.2
	FLO-5	83.1	84.1	94.9	95.8
	FLO-6	80.2	88.2	98.3	97.1
Messmer's UV Plus (Natural)					
	MES-1	81.8	80.3	71.5	69.8
	MES-2	80.3	77.9	80.2	88.8
	MES-3	76.2	77.4	78.5	80.3
	MES-4	92.5	88.4	72.3	73.6
	MES-5	72.8	71.2	62	60.8
	MES-6	68.8	69.4	70.2	70.7

Table 8. Contact Angle Measurements of both sides of the water droplet on samples before and after weathering.

Control

The control, both pre- and post-weathering, starting absorbing the water droplets almost immediately, limiting the ability to get correct contact angles. This is in accordance with the hydrophilic nature of wood along with the samples' low moisture contents, however, and is to be expected. Even so, contact angles increased drastically after weathering in all samples except for 6.

Allbäck Boiled Organic Linseed Oil

The linseed oil coatings appear to have retained much of their hydrophobicity even after weathering. The angle measurements remained roughly the same or even decreased after weathering. Sessile drops remained proud of the surface even after thirty seconds on almost all samples, weathered and un-weathered. Sample 6 was an exception to this observation and the drop appeared to sink into the surface more after only ten seconds.

Paraffin and Mineral Spirits

The paraffin coating had obviously degraded during weathering and had lost its hydrophobicity. Drops placed on the weathered surfaces sank into the wood substrate almost immediately and were unable to be measured in certain cases. Drops on the pre-weathered surfaces, however, sat high on the surface and were stable. Samples 4 and 5 had cupped surfaces so the measurements for post-weathering were largely void.

DEFY Extreme Exterior Clear Wood Stain

DEFY didn't appear to have much of a change in hydrophobicity after weathering; most of the samples had slightly increased angles with a few decreased value. The coating displays some hydrophobic qualities but, for the most part, angles were not as high as those seen in linseed oil or the un-weathered paraffin.

Armstrong's Wood Stain for Decks (Natural Tone)

The drops places on the Armstrong-Clark-coated weathered wood appear to have a fairly low contact angle, but began to settle after about ten seconds into a lower angle. However, they are not absorbed into the wood like those seen on the control or the weathered paraffin and mineral spirits coating. In comparing the pre- and post-weathering surfaces, the product appears to have retained the same level of hydrophobicity, the contact angles increasing only by about 10-20˚.

TWP 1500 Series Natural Stain (Natural Tone)

Both the pre- and post-weathered surfaces of the TWP-treated samples are very hydrophobic, with some of the lowest angles of contact in both sections. The water droplets stood very high above the surface and remained this way after over thirty seconds, even on the roughened surface.

Flood CWF-UV 5 Penetrating Wood Finish for Fences, Decks, and Siding (Natural Tone (Clear))

The hydrophobicity of the Flood treatment appears to have been affected by the weathering. The water droplets spread out rather quickly across the wood surface.
The coating before weathering appears to be fairly hydrophobic, but the angle visibly decreased in the weathered samples and contact angle values confirm this shift of 20-30˚ on some samples.

Messmer's U.V. Plus Exterior Wood Finish (Natural)

The samples treated with Messmer's UV Plus appear to have retained the hydrophobic qualities of the treatment and in certain samples the contact angles decreased by about 10˚

after weathering. The droplets appear much the same on both the pre- and post-weathering samples.[18]

T-test

The paired (dependent) t-test was used to compare the mean percent angle change for each cohort samples by comparing the contact angle measurements on the un-weathered surfaces to those taken on weathered surfaces. The values were calculated using a data analysis plug-in on Microsoft Excel[19] based off of the equation mentioned previously in Section 3.5. Based off of the calculations and comparing the t Stat value to the t Critical value[20] at a 95% confidence interval at 5 degrees of freedom, the null hypothesis was accepted for almost all of the samples, indicating that there was not a difference in the mean between the initial angle measurements and the measurements after weathering. However, the left angle of the linseed oil sample, failed the test with the critical value (2.13184679) was less than that of the t stat value (2.51723465). Thus, for this sample, there was a difference in the mean between the initial angle measurements and the measurements after weathering.

[18] Messmer's advertises that water does not bead on its surface because they do not add waxes or paraffin to their stain because they are not good permanent water repellents and interfere with adhesion for further coatings like paints. The high solids content that fills the pores of the wood is supposed to protect against water infiltration.
[19] Calculations can be found in Appendix G.
[20] If the t stat value is less than the t critical value then the null hypothesis is accepted, if it is the opposite than the null hypothesis is accepted.

Sample		Left Angle	Right Angle
Control	t Stat	-3.8661949	-2.1222655
	t Critical	2.13184679	2.13184679
	Pass / fail?:	**pass**	**pass**
Linseed Oil	t Stat	2.51723465	1.03982978
	t Critical	2.13184679	2.13184679
	Pass / fail?:	**fail**	**pass**
Paraffin and Mineral Spirits	t Stat	-3.257006	-2.9743208
	t Critical	2.13184679	2.13184679
	Pass / fail?:	**pass**	**pass**
DEFY Extreme (Clear)	t Stat	-1.47785	-1.4786087
	t Critical	2.13184679	2.13184679
	Pass / fail?:	**pass**	**pass**
Armstrong (Natural)	t Stat	-1.9140455	-1.6685677
	t Critical	2.13184679	2.13184679
	Pass / fail?:	**pass**	**pass**
TWP 1500 (Natural)	t Stat	-0.132254	-0.5959862
	t Critical	2.13184679	2.13184679
	pass/fail?:	**pass**	**pass**
Flood CWF UV-5 (Natural)	t Stat	-3.0560729	-2.8516753
	t Critical	2.13184679	2.13184679
	pass/fail?:	**pass**	**pass**
Messmer's UV Plus (Natural)	t Stat	1.25425089	0.43278141
	t Critical	2.13184679	2.13184679
	pass/fail?:	**pass**	**pass**

Table 9. T-test values for the change in contact angle measurements before and after weathering.

4.3 Treatment Retention

As previously mentioned in section 4.1.4 of this chapter on using FTIR for sample analysis, in this experiment FTIR is being used as a qualitative rather than a quantitative analysis. This judgement stems from the unknown compositions of most of the treatments. Though the relative concentrations and identities of the components are still unknown, by appraising the spectra of the un-weathered and weathered treated samples, the presence, or lack thereof, of the treatment in the surface fabric can be indicated.

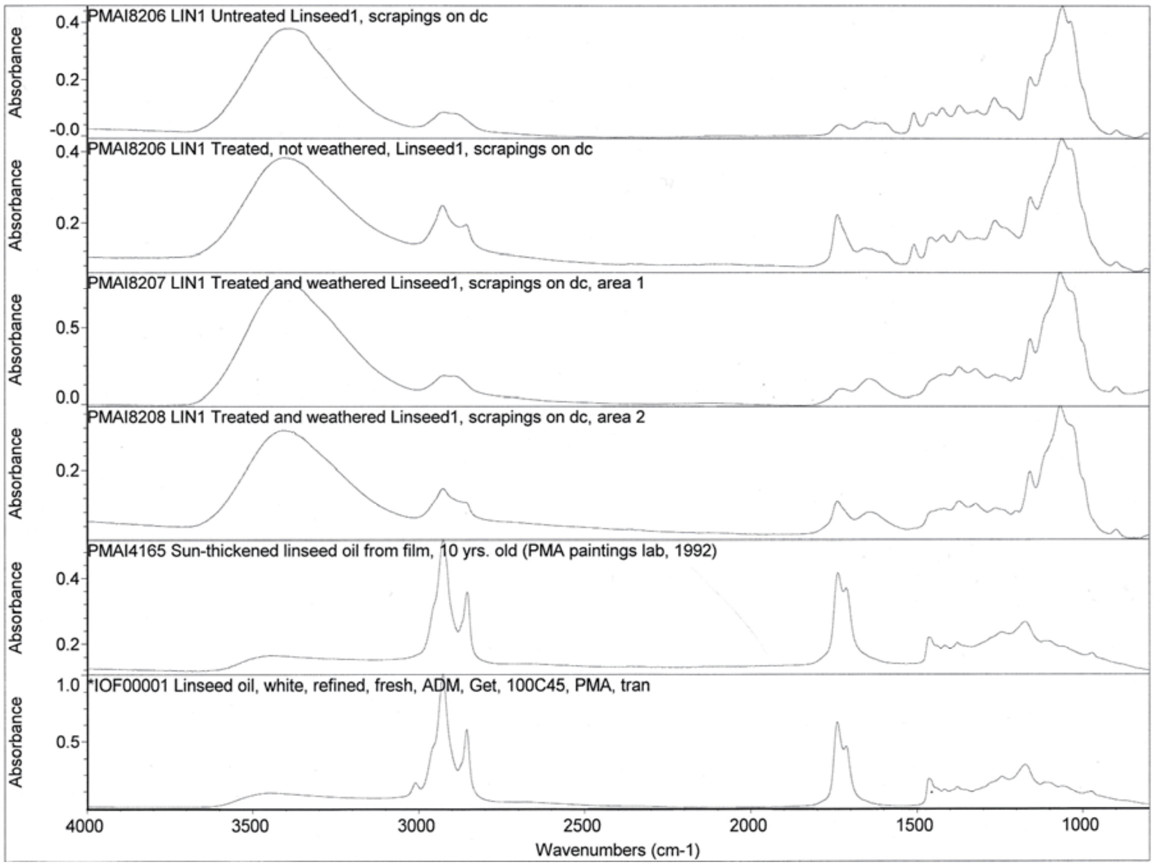


Figure 55. The spectra for the linseed oil treatment before and after weathering with standard spectra for both fresh and 10-year-old linseed oil for comparison. Generated at the Philadelphia Museum of Art.

Though the intensities of the peaks that appear to indicate the presence of linseed oil are much reduced from the pre-weathered surface to both post-weathered sampling areas, there appears to be linseed oil still remaining in the surface fabric of sample 1. The spectra for the paraffin and mineral spirits treatment does not appear to show much of an indication of any additive to the surface wood material confirming the earlier assessment that the very small amount of paraffin in the reduced recipe was not enough to deposit on the wood to protect it.[21] As mentioned in section 4.1.4, the DEFY product appears to remain on the surface of the wood after weathering, but the action of weathering also may have generated an acrylic-based

[21] If paraffin in mineral spirits is to be pursued then the concentration of paraffin in the mixture must be increased.

degradation product or at least intensified its presence on the wood surface. The peaks from pre- and post-weathering are much the same, though the peaks of the weathered sample are much more intense. The sample treated with Armstrong's Wood Stain appears to have retained the product in it surface material as well, for the peaks are not much reduced from weathering. The TWP treated sample appears to have retained its treatment and also possibly gained another component during weathering. Subtraction of the spectrum of uncoated, un-weathered wood from the spectrum of the treated and weathered sample gave some insight into what this new component could be; the analysis program indicated the presence of whewellite, a type of calcium oxalate weathering that can occur when a calcium source is present. The TWP coating likely contains a calcium drier.

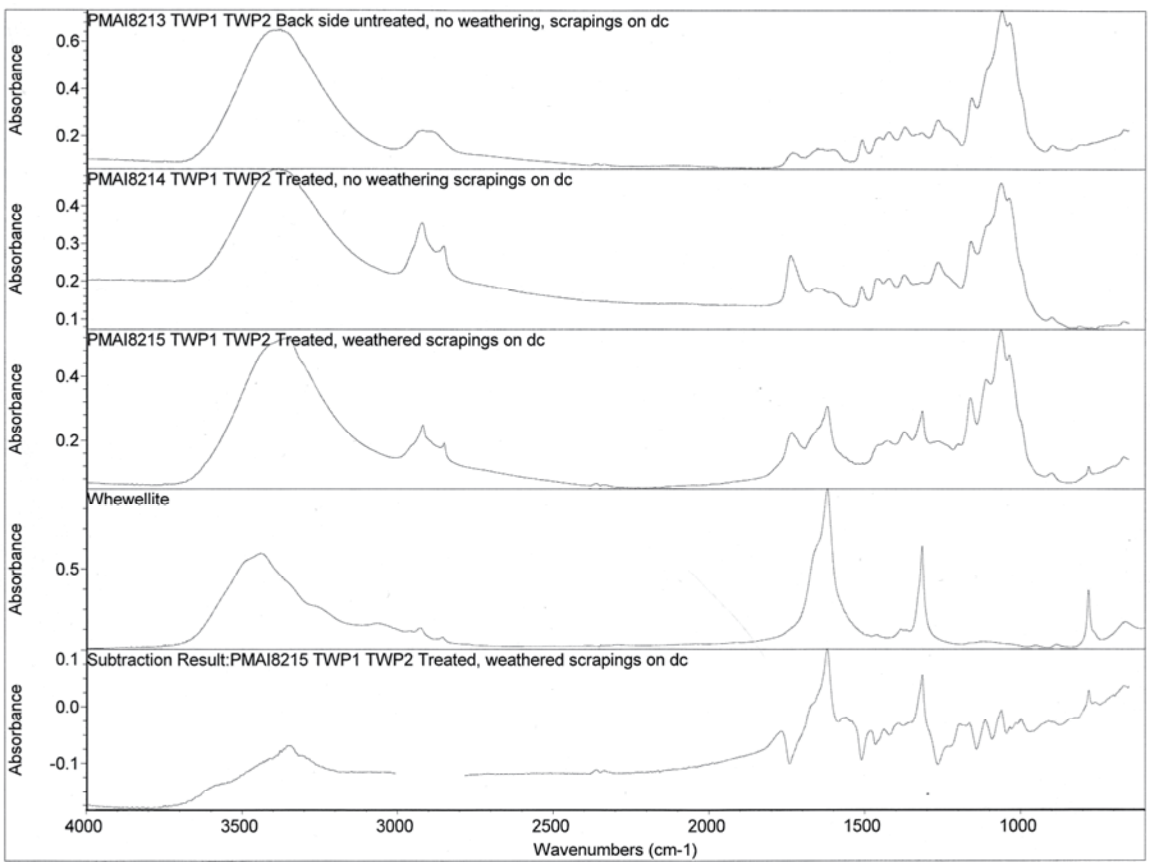


Figure 56. Spectra of TWP 1500 Series (natural) showing before and after weathering as well as the subtracted spectrum and the suggested spectrum match of whewellite. Spectra generated at the Philadelphia Museum of Art.

The Flood sample appears to have retained its surface treatment during weathering, though some of the peaks appear to be less intense in places. Finally, the spectra of Messmer's UV Plus appear to be much the same before and after weathering, with only a slight decrease in intensity of most peaks and the lignin peak missing at 1508 wavenumbers. Comparisons with spectra of both new and aged linseed oil suggest that this oil is one of the components of the treatment.

Future analysis using FTIR for coated samples before and after weathering should include testing of cured weathered samples to determine their spectra. These spectra could both be used for insight into the weathering process of the coatings by themselves as well as for subtraction from the spectra of the weathered treated wood samples in order to determine how just the wood changed during weathering rather than the wood plus the coating.

4.4 Product Performance

New wood exposed to weathering gradually changes color, becomes rough and loses fibers, and develops microchecks that can eventually turn into cracks. Additionally, the dimensional stability of the pieces can alter and pieces can warp, and especially cup in the case of this experiment. Weathered wood samples often take on a silvery light gray appearance when microorganisms are absent due to the layers of mostly cellulose on the surface absent of lignin degradation products. All of these symptoms of weathering were observable in this experiment; sample cohorts were evaluated for signs of physical degradation every one hundred hours to monitor their progress as the weathering proceeded.

Hours	Date	Time	Cycle	Point in Cycle
100	3/8/15	10:30 PM	condensation	2 hours into cycle
200	3/13/15	2:31 AM	condensation	3 hours into cycle
300	3/17/15	9:00 AM	condensation	30 minutes into cycle
400	3/21/15	3:00 PM	ultraviolet	30 minutes into cycle
500	3/25/15	7:00 PM	ultraviolet	3 hours 30 minutes into cycle
600	3/30/15	12:35 AM	condensation	3 hours 15 minutes into cycle
700	4/3/15	7:30 AM	condensation	1 hour into cycle
800	4/7/15	12:30 PM	condensation	3 hours into cycle

Table 10. Times and cycles at which samples were taken out roughly at every 100 hour monitoring period.

Terms relating to degradation were derived from ASTM D9-12 – Standard Terminology Relating to Wood and Wood-Based Products. Commonly used terms in these evaluations include:

- **Check** – a separation of the wood along the fiber direction that usually extends across the rings of annual growth, commonly resulting from stresses set up in wood during seasoning.
- **Cup** – a distortion of a board in which there is a deviation flatwise from a straight line across the width of the board.
- **Earlywood** – the less dense, large-celled, part of the growth layer formed first during the annual growth cycle; a synonym for springwood.
- **Face** – the wide surface of rectangular pieces of lumber. Often the surface that determines the grade of lumber destined for remanufacture.
- **Flat grain** – the grain pattern resulting when lumber has been sawed in a plane approximately perpendicular to the radius of the log.
- **Grain** – the direction, size, arrangement, appearance, or quality of the fibers in lumber or other wood products.

- **Latewood** – the denser, smaller-celled, later-formed part of a growth layer; a synonym is summerwood.
- **Mineral streak** – an olive to greenish-black or brown discoloration of undetermined cause; commonly associated with bird pecks and other injuries.
- **Sapwood** – the wood containing some living cells and forming the initial wood layer beneath the bark of the log.
- **Split** – a separation of the wood parallel to the fiber direction, due to the tearing apart of the wood cells.
- **Stain** – a discoloration in wood that may be caused by such diverse agencies as microorganisms, metal, or chemicals.
- **Warp** – any variation from a true or plane surface. Warp includes bow, crook, cup, and twist, or any combination thereof.

Additional terms used in description of the degradation of the wood surfaces include surface roughening, when fibers on the surface of the wood begins to break away from the substrate, and rising grain, when the less dense earlywood is eroded off faster than the dense latewood causing ridges on the surface.

Figure 57. Example of the typical symptoms exhibited by a weathered sample. This sample has checks ranging from very small to large, a roughened earlywood surface, and raised latewood grain. Color change is apparent at the bottom of the photograph from where the bracket covered the sample and protected it from UV degradation. Photograph by author.

At the end of the experiment, the weathered samples were evaluated within their cohorts to determine how each performed. Each sample was given a rating out of five relative to the other samples within its cohort: 1 bad, 2 poor, 3 fair, 4 good, and 5 excellent. Below is a summary of the degradation symptoms as the samples progressed during weathering by arranged by cohort followed by the ratings of each sample within the cohort according to its performance after eight hundred hours of weathering.

Control

Checks evolved in the substrate of samples 1-4 early in the weathering process. By 100 hours, these samples had checks and were warping in the machine. By 300 hours, a larger check was evolving in sample 2 and samples 3-4 had a roughened surface on the earlywood with a white sheen. This roughening progressed throughout the rest of the weathering, spreading to samples 5 and 6 by 500 hours and 1 and 2 by 600 hours. The checks in the surfaces continually got bigger and spread as weathering continued and all of the samples were warped to some extent by the end of the weathering cycles.

The curved sample evolved some small checks by 200 hours and acquired a rough surface and some irregular staining by 300 hours. The checks became larger by 500 hours, and a silvered surface was first noticed at the 600 hour mark with other areas of darker staining on the surface.

Evaluation of weathered samples:

- Sample 1 has a variety of small to medium checks in its fabric. The surface is lightly silvered in the earlywood sections with some light roughening and a few concentrated spots of white-grey fabric on the earlywood. The sample has not cupped. **(Rating – 3, Fair)**
- Sample 2 has a variety of smaller checks as well as a larger check that has bisected the wood substrate and partially split the wood. The surface is silvered and the earlywood rough with raised latewood grain. The sample appears to not have cupped very much. **(Rating – 2, Poor)**
- Sample 3 has several medium-sized checks. The surface is silvered with many small spots seen across the surface in raking light. The earlywood is rough and the latewood grain is raised. The sample has visible cupping. **(Rating – 2, Poor)**
- Sample 4 has a large number of checks ranging from small to medium. The latewood grain is raised and the earlywood grain is silvered and fairly roughened. The same spots visible in raking light are present. The sample is cupped. **(Rating – 2, Poor)**
- Sample 5 has only a few small checks. The surface is silvered with raised latewood grain and the sample has cupped slightly. The small spots are visible in raking light. **(Rating – 4, Good)**

- Sample 6 has only a few small checks as well. The surface is silvered with the small spots visible in raking light. The grain of the latewood is raised and the earlywood is lightly roughened. The sample is lightly cupped. **(Rating – 4, Good)**
- The curved sample has a sheen in a few areas of the surface, especially the area that has silvered to a gray tone. The other portion of the wood is a light brown-yellow. The surface has many small to large checks and is fairly rough.

Sample	1 - Bad	2 - Poor	3 - Fair	4 - Good	5 - Excellent
CON-1			X		
CON-2		X			
CON-3		X			
CON-4		X			
CON-5				X	
CON-6				X	

Table 11. Comparison of sample performance within control cohort.

Allbäck Boiled Organic Linseed Oil

The linseed oil samples were largely unaffected by weathering, besides some warping, until the 300 hour mark when it was noted that the surfaces had roughened, small checks had formed, and the surface had visibly darkened. There were small checks in all of the samples by 500 hours and those had grown larger by 700 hours with most of the earlywood areas showing lightly roughened surfaces.

The curved sample showed signs of checking and color change by the 300 hour mark as well. The sample continually roughened and the checks grew in size throughout the weathering. Observations at the 700 hour mark noted that the checks were very large and the surface was very rough and had a white sheen.

Evaluation of weathered samples:

- Sample 1 has a few small checks in its surface. The surface has a sheen and small dots can be seen throughout the fabric in raking light. The earlywood and latewood are both roughly the same color and there is slightly raised grain. Some surface roughening and some cupping. **(Rating – 3, Fair)**

- Sample 2 has a few small checks and has the same surface sheen with small spots visible in raking light. The grain is slightly raised with light surface roughening. The sample is only slightly cupped. **(Rating – 3, Fair)**
- Sample 3 has a slight sheen with only a few spots. The earlywood is much lighter than the latewood and more silver. The surface is fairly rough with raised grain. The sample has a small amount of cupping and a few small checks. **(Rating – 2, Poor)**
- Sample 4 has a silvered sheen with spots visible in raking light. The surface only has a few very small checks. The earlywood is more silvered than the latewood and has a roughened surface. The grain is lightly raised and the sample slightly cupped. **(Rating – 4, Good)**
- Sample 5 has a fairly rough and shiny surface with a few small checks in the surface. The grain is lightly raised and the sample appears to not have warped in weathering. **(Rating – 3, Fair)**
- Sample 6 has a shiny surface with only a few small checks. Small spots are visible in raking light. The grain is lightly raised and the earlywood lightly roughened. The sample appears to have not warped in weathering. **(Rating – 4, Good)**
- The curved sample has a fairly rough surface with a fine, white powdery surface in some areas and surfaces with sheen in other parts. The sample has a few areas where the wood is darker as well. There are small to medium-sized checks across the surface.

Sample	1 - Bad	2 - Poor	3 - Fair	4 - Good	5 - Excellent
LIN-1			X		
LIN-2			X		
LIN-3		X			
LIN-4				X	
LIN-5			X		
LIN-6				X	

Table 12. Comparison of sample performance within linseed oil cohort.

Paraffin and Mineral Spirits

Checking as well as warping was noted in all samples but sample 6 by the 100 hour mark for the paraffin and mineral spirits treatment. The checks grew in size and surface became visibly rough by 300 hours, especially in samples 1 and 2. The severity of the checks as well as the rough earlywood surfaces continued to grow as weathering progressed and all samples warped by the end of the experiment.

The curved sample developed checking by 200 hours that developed into larger checks with a rough, splotchy surface by 500 hours and continued to degrade as weathering progressed.

Evaluation of weathered samples:

- Sample 1 has a very rough surface with visible flakes of wood fabric lifting off of the substrate. The earlywood is much more roughened than the darker latewood though the grain is not very raised. The surface is silvered and has spots visible in raking light. There are several large checks. The sample does not appear to have warped. **(Rating – 1, Bad)**
- Sample 2 has a very rough surface with visible flakes of wood fabric lifting off of the substrate. The latewood grain is slightly raised and the earlywood is very rough and silvered with spots visible in raking light. The surface is entirely covered in check

ranging from small to large and the sample appears to have been almost split by a check. The sample appears not to have warped. **(Rating – 1, Bad)**

- Sample 3 has a silvered surface with spots visible in raking light. The earlywood surface is fairly smooth. The grain is slightly raised and a few small to medium-sized checks range up the left side of the sample. The sample cupped during weathering. **(Rating – 3, Fair)**
- Sample 4 has a silvered surface with the spots visible in raking light. The sample has some medium-sized checks and the grain is slightly raised. The earlywood surface appears fairly smooth. The sample cupped slightly **(Rating – 3, Fair)**
- Sample 5 has a silvered surface and shows the same spots in raking light but the surface is a darker color than the previous samples. The grain is raised fairly high. A few medium-sized checks are on the surface. The sample does not appear to have warped. **(Rating – 3, Fair)**
- Sample 6 has a silvered surface with the spots in raking light as well, but it appears to be the darkest color of all of the samples. There is a dark streak, perhaps a stain, on the left side. The grain is raised and the earlywood surface is fairly smooth. The sample appears to not have warped. **(Rating – 4, Good)**
- The curved sample has a very shiny silvered surface with a large dark brown stain. The surface is fairly rough with large checks running through the fabric fairly deeply.

Sample	1 - Bad	2 - Poor	3 - Fair	4 - Good	5 - Excellent
PAR-1	X				
PAR-2	X				
PAR-3			X		
PAR-4			X		
PAR-5			X		
PAR-6				X	

Table 13. Comparison of sample performance within paraffin and mineral spirits cohort.

DEFY Extreme Exterior Clear Wood Stain

The samples treated with DEFY began to show signs of weathering by the 100 hour mark. Samples 3 and 5 had checks, and the check in 3 worsened by 200 hours. By 300 hours, the surfaces of samples 1, 2, 5, and 6 had roughened and checks spread to all samples. The surfaces of the samples continued to roughen and checks gradually increased in size as the weathering proceeded. The gray discoloration on sample 3 was first noticeable by 600 hours and continued to lighten. By the end of the weathering process, all of the samples had rough surfaces and had warped.

The curved sample began to develop checks by 200 hours and the surface was noticeably roughened by 400 hours. The checks continued to grow in size throughout weathering and the surface roughened, the coloring remained fairly consistent across the sample.

Evaluation of weathered samples:

- Sample 1 has and extremely rough surface on both the earlywood and latewood with loose wood fibers and there are small to large sized checks throughout. The surface has a slight sheen. The earlywood and latewood are roughly the same colors. The sample does not appear to have warped. **(Rating – 1, Bad)**
- Sample 2 has an extremely rough surface as well with multiple medium to large checks that split the substrate in places. The surface has a slight sheen. The earlywood and latewood are roughly the same color. The sample does not appear to be warped. **(Rating – 1, Bad)**
- Sample 3 has a slightly shiny surface with a lightly roughened surface on the earlywood especially. The sample has a few checks and slightly raised grain. There is

a lighter, grayer portion of the surface on the left side. The sample appears to have slightly cupped. **(Rating – 1, Bad)**

- Sample 4 is slightly shiny with a few medium-sized checks in the surface. The grain is slightly raised and the earlywood is roughened. The sample has a gray sheen along the left side that appears to have discolored it. The sample appears to have slightly cupped in weathering. **(Rating – 2, Poor)**
- Sample 5 has a fairly evenly colored surface with the earlywood and latewood being roughly the same light tan color. There are only a few small checks in the surface. The grain is raised and the earlywood surfaces roughened. The sample appears not to have warped. **(Rating – 4, Good)**
- Sample 6 has an evenly colored surface with the earlywood and latewood portions being roughly the same color. The earlywood surfaces are roughened and the latewood grain is raised. There are only a few very small checks in the surface. The sample does not appear to have warped at all in the weathering process **(Rating – 5, Excellent)**
- The curves sample has a fairly roughened surface with some areas of shiny fabric. The color, a light yellow-brown is uniform across the surface. Several medium-sized checks run across the surface.

Sample	1 - Bad	2 - Poor	3 - Fair	4 - Good	5 - Excellent
DEF-1	X				
DEF-2	X				
DEF-3	X				
DEF-4		X			
DEF-5				X	
DEF-6					X

Table 14. Comparison of sample performance within DEFY Extreme cohort.

Armstrong's Wood Stain for Decks (Natural Tone)

Samples 5 and 6 showed signs of checks and warping at the first 100 hour monitoring period and all of the samples appeared to have small checks by the 300 hour mark. These checks continued to grow in size throughout the weathering, especially those on samples 5 and 6. The earlywood areas of the samples began to show roughness by 400 hours especially on samples 1, 2, 5, and 6. There was very little warping in the samples throughout the experiment. All samples appeared to have darkened by the 300 hour mark.

The curved sample did not show surface roughening until the 300 hour mark. The surface continued to roughen and discolor in places, eventually developing darker patches as well as patches of silvery discoloration. Small checks began to appear at 400 hours and grew slightly, but did not increase in number.

Evaluation of weathered samples:

- Sample 1 has a slight sheen and a few small to medium checks in the surface. The earlywood is roughened and the grain is slightly raised. The sample appears to have slightly cupped. **(Rating – 2, Poor)**
- Sample 2 has a slight sheen and some very small checks. The surface is only lightly roughened and the grain slightly raised. The sample does not appear to have warped in weathering. **(Rating – 5, Excellent)**
- Sample 3 has a slight sheen to the surface and only a few small checks. The earlywood appears to only be lightly roughened. The grain is slightly raised. The sample appears to have slightly cupped in weathering but is now flat. **(Rating – 5, Excellent)**

- Sample 4 has a slight sheen to the surface with some small to medium-sized checks. The grain is slightly raised and there is some light roughening of the earlywood surface. The sample appears to have slightly cupped. **(Rating – 4, Good)**
- Sample 5 has a slight sheen on the earlywood portions mostly. The earlywood portions are roughened and the grain is raised. There are some medium-sized checks across the surface that extend through the bottom of the wood substrate. The sample appears to have cupped in weathering. **(Rating – 2, Poor)**
- Sample 6 has a sheen to the surface. The earlywood surface is roughened and some fabric comes off when brushed. The grain is slightly raised and medium-sized checks are concentrated mostly on the right side and extend through the wood substrate. The sample appears to be flat. **(Rating – 2, Poor)**
- The curved sample has a roughened, matte surface. The coloring is a bit irregular with darker staining in certain areas and along some checks. Small checks can be seen on the surface.

Sample	1 - Bad	2 - Poor	3 - Fair	4 - Good	5 - Excellent
ARM-1		**X**			
ARM-2					**X**
ARM-3					**X**
ARM-4				**X**	
ARM-5		**X**			
ARM-6		**X**			

Table 15. Comparison of sample performance within Armstrong's Wood Stain cohort.

TWP 1500 Series Natural Stain (Natural Tone)

Checks began to appear in samples 3 and 4 at the 100 hour mark and appear to have grown slightly throughout weathering with checks developing in samples 5 and 6 by 300 hours and samples 1 and 2 by 600 hours. The surfaces were noticeably roughened by 400 hours, especially on samples 3 and 4. Warping in all samples as well as noticeable darkening with a slight orange hue was noticeable by 300 hours. A small discolored spot first appeared on sample 4 at 500 hours and grew darker than the rest of the fairly even-toned sample for the rest of the weathering.

The curved sample developed a rough surface by 300 hours and began to develop a blotchy appearance by 500 hours with orange-brown-toned patches. Tiny checks appeared by 600 hours, but did not expand as weathering continued.

Evaluation of weathered samples:

- Sample 1 has a slight sheen to the surface and only a few small checks. The grain is slightly raised and the earlywood areas are slightly roughened. The earlywood and latewood portions are very similar in color. There is a darker brown stain down the left side of the sample. The sample appears to have cupped slightly in weathering. **(Rating – 4, Good)**
- Sample 2 has a very slight sheen to the surface. There are only a few very small checks in the surface. The earlywood and latewood are very similar in coloring and the grain is slightly raised. The earlywood is lightly roughened. The sample appears slightly cupped. **(Rating – 5, Excellent)**
- Sample 3 has a slight sheen to the surface. The earlywood surface is incredibly rough and the latewood surface is lightly roughened. The latewood grain is raised and medium to large checks run throughout the sample surface, almost splitting the substrate. The sample appears fairly flat. **(Rating – 1, Bad)**
- Sample 4 has a slight sheen to the surface. The earlywood surface is very rough and the latewood surface is lightly roughened. There are checks ranging from small to medium throughout the surface and one small checks is surrounded by darker

brown staining. The grain is raised and the sample appears to be lightly cupped. **(Rating – 1, Bad)**

- Sample 5 has a slight sheen with spot visible in raking light. The earlywood surface is roughened and the grain raised. A few medium-sized checks are along the right side. The earlywood and latewood appear to be basically the same color. The sample is slightly cupped. **(Rating – 3, Fair)**
- Sample 6 has a slight sheen with some spots visible in raking light. The surface is roughened more in certain places than others though mostly on the earlywood. There are some medium-sized checks running up the right side of the sample. The sample is slightly cupped. **(Rating – 3, Fair)**
- The curved sample has a very splotchy surface. Some areas are lighter than others but the whole surface is roughened and matte. Only a few very small checks can be seen on the surface.

Sample	1 - Bad	2 - Poor	3 - Fair	4 - Good	5 - Excellent
TWP-1				X	
TWP-2					X
TWP-3	X				
TWP-4	X				
TWP-5			X		
TWP-6			X		

Table 16. Comparison of sample performance within TWP 1500 Series cohort.

Flood CWF-UV 5 Penetrating Wood Finish for Fences, Decks, and Siding (Natural Tone (Clear))

Small checks began to develop in samples 1, 2, and 3 by 200 hours, while samples 5 and 6 exhibited checking starting at 400 hours. All surfaces appeared to roughen starting at 300 hours along with noticeably darkening towards an orange-brown tone. Though the surface was roughened, there were no white patches as seen on the other samples; the samples were all generally the same color, both earlywood and latewood. Raised latewood grain was especially noticeable on samples 1 and 2 starting at 600 hours.

The curved sample appeared to turn a darker, more orange tone by 300 hours. The surface began to show roughening and small checks by 400 hours that grew larger throughout the weathering process. The sample had a few patches of shiny surface material by the 700 hour mark.

Evaluation of weathered samples:

- Sample 1 has a slight sheen to the surface. The surface is very roughened in the earlywood sections and the grain is raised. The earlywood and latewood are roughly the same color. There are a few small checks in the surface. The sample appears slightly cupped. **(Rating – 3, Fair)**
- Sample 2 has a slight sheen. The earlywood surface is very rough and the grain raised. There are only a few medium-sized checks in the surface. The earlywood and latewood are roughly the same color. The sample is very slightly cupped. **(Rating – 3, Fair)**
- Sample 3 has a very slight sheen to the surface. The earlywood portions are very rough. A medium-sized check splits the substrate. The grain of the latewood is raised. The earlywood and latewood are about the same color. The sample is slightly cupped. **(Rating – 2, Poor)**
- Sample 4 has a slight sheen to the surface. The earlywood and latewood are roughly the same color and the earlywood is roughened in some places. The sample has raised grain and a few medium-sized checks. The sample is slightly cupped. **(Rating – 3, Fair)**

- Sample 5 has a slight sheen to the surface. The earlywood sections are extremely rough and the latewood portions slightly rough. The grain is slightly raised and medium-sized check run down the middle of the sample. The earlywood and latewood sections are roughly the same color. The sample is slightly cupped. **(Rating – 1, Bad)**
- Sample 6 has a slight sheen to the surface and the earlywood and latewood are roughly the same coloring. The earlywood is extremely weathered and the grain is slightly raised. Medium-sized checks run down the middle of the sample. The sample appears flat. **(Rating – 1, Bad)**
- The curved surface is fairly rough and matte. The entire surface is a fairly consistent color with little variation in reaction, only a few small shiny spots. There are a few small to medium-sized checks in the surface.

Sample	1 - Bad	2 - Poor	3 - Fair	4 - Good	5 - Excellent
FLO-1			X		
FLO-2			X		
FLO-3		X			
FLO-4			X		
FLO-5	X				
FLO-6	X				

Table 17. Comparison of sample performance within Flood CWF-UV 5 cohort.

Messmer's U.V. Plus Exterior Wood Finish (Natural)

Samples 3, 4, 5, and 6 exhibited first signs of very small checks as well as warping by 100 hours. Surfaces appeared rough by 300 hours, especially on samples 1, 2, 3, and 4, and all sample exhibited slight warping. Checks in samples 3, 4, 5, and 6 expanded by 500 hours and by 700 hours these checks had become large. Lighter patches developed on the surfaces by 500 hours, and a dark streak appeared on sample 5 at the 600 hour mark and remained throughout the duration of weathering.

The curved sample exhibited small checks and a rougher, more brown-orange tone by 300 hours. The checks remained small throughout weathering and the coloring of the surface material appeared fairly regular through the end of the experiment.

Evaluation of weathered samples:

- Sample 1 has a sheen to the surface with visible spots in raking light. The earlywood is very rough and the latewood is slightly rough. The grain is raised and a few small checks are on the surface. The earlywood and latewood sections are roughly the same color. The sample is slightly cupped. **(Rating – 1, Bad)**
- Sample 2 has a surface sheen with visible spots in raking light. The earlywood surface is lightly roughened and the grain is raised. There are only a few very small checks on the surface. The earlywood and latewood are roughly the same coloring. The sample is slightly cupped. **(Rating – 4, Good)**
- Sample 3 has a sheen to the surface. The earlywood portions are very rough and the latewood portions slightly roughened. The grain is slightly raised. There are medium-sized checks on the surface and the sample is slightly cupped. **(Rating – 1, Bad)**
- Sample 4 has a surface sheen and the earlywood portions are extremely roughened while the latewood portions are lightly roughened. The grain is raised slightly and small to medium-sized checks are visible on the surface. The sample is slightly cupped. **(Rating – 1, Bad)**
- Sample 5 has a sheen to the surface and spots are visible in raking light. The earlywood portions of the surface are fairly roughened and the grain is raised. There are medium-sized checks across the surface and a darker stain streaked down the middle of the sample. The sample is slightly cupped. **(Rating – 2, Poor)**

- Sample 6 has a sheen to the surface and spots are visible in raking light. The earlywood surfaces are lightly roughened and a few medium-sized checks are visible on the surface. The grain is slightly raised. The earlywood and latewood are roughly the same color. The sample is slightly cupped form weathering. **(Rating – 3, Fair)**
- The curved sample has a fairly rough surface with some small checks. The discolored streak across the length of the sample originates from natural wood staining at the beginning of the experiment and does not appear to have been affected by the weathering. The surface is a red-brown color and appears matte.

Sample	1 - Bad	2 - Poor	3 - Fair	4 - Good	5 - Excellent
MES-1	X				
MES-2				X	
MES-3	X				
MES-4	X				
MES-5		X			
MES-6			X		

Table 18. Comparison of sample performance within Messmer's UV Plus cohort.

Chapter 5: Conclusions

In creating a long-term maintenance plan for log structures, both the efficacy of the treatment against degradation and the aesthetics of the site have to be considered. The treatments must allow the new log replacements to weather and match the extant fabric while also protecting that historic fabric from degrading further. The ideal conservation treatment would create this uniform appearance and be compatible with both weathered and new replacement logs, environmentally-friendly, affordable, and reversible or at least re-treatable. Finding a treatment that fits all of these criteria is difficult, but observations and tests from this accelerated weathering experiment has given insight into the behavior of a small selection of possible solutions. In analyzing the results of this experiment, several factors had to be taken into consideration:

- Wood is an incredibly variable material and not all samples behave in the same manner both in the lab and on site. This is especially applicable for historic wood where years of weathering may have affected the properties of the wood fabric differently both within the same log as well as between logs.
- Conditions in the Weatherometer did not exactly match those that the samples would experience in Grand Teton National Park; the purpose of accelerated weathering is to identify characteristic responses of degradation and failure across cohorts of samples.
- The samples tested were flat and not rounded like those found on the site. Though some curved samples were tested for comparison, ideally full round logs should be tested on site to see how the treatments compare.
- Tests were conducted on only one grain orientation due to time and space restrictions. The transverse grain especially should be tested alongside the tangential grain to better understand the needs of the sites because many log structures have exposed log ends

from their construction methods. Additionally, the transverse grain often weathers differently because it can allow a greater depth of UV radiation penetration as well as greater water penetration.

- Many of the new logs installed for replacements have bark or remnants of bark on their exteriors that would inhibit acceptance of the treatments; removal of this bark for treatment, however, would expose the more sensitive sapwood to weathering. Additionally, the extant logs were previously covered in bark that has since weathered away on the exteriors. The logs, at least on the Bar BC Ranch, also had been treated with oil, likely linseed oil, and might not accept certain treatments, especially water-based ones. These conditions may lead to recommendations either for allowance of natural weathering of new surfaces for a prescribed amount of time to remove the bark before treatment or a maintenance cycle that removes the bark prematurely for treatment.
- Conservators have to decide whether the weathered surfaces of the extant logs can be removed as advised by the product guides or not. Removal of soiling and loose fibers on the weathered surface can allow for an even penetration and greater stability of the treatments, but these surfaces consist of original fabric and have become part of the aesthetic of the site since the bark weathered off long ago. This must be taken into consideration in terms of the treatment of historic fabric in conjunction with the treatment of new fabric. The aesthetics of the weathering process of each should approach the same result.
- Tests have not yet been conducted on weathered wood from the sites in the Grand Teton region, so an exact tolerance for color change cannot be officially determined in this paper but the coloring of the logs can be estimated from previous site visits and photographs. Most logs range from a silvered light brown to dark red-brown surface

depending upon which elevation they are located and the weathering exposure of those elevations.

Figure 58. Extant Logs found at the Bar BC Dude Ranch displaying a range of coloration. Photograph by Christine Leggio for the Bar BC Condition Assessment and Report, 2011 by the Architectural Conservation Laboratory.

- The samples were only exposed to 800 hours of weathering. While this was a long enough time period to effectively deteriorate the wood and see how the products performed, the length of time should ideally reach industrial standards of 1000 or 1500 hours or even longer both for results comparison as well as to push the limits of the samples even further.
- Since the samples were taken out at each 100 hour and the cycles varied for these monitoring periods, the results of readings for coloring and weight were inconsistent and no trend line for weight loss or discoloration could not be charted to estimate the

effects of longer weathering. As mentioned previously, in future testing this should be addressed and different monitoring intervals established.

- Since the cut of the growth rings is not very visible on logs as compared to flat boards, aesthetic differences that the treatments may have on earlywood vs latewood (eg. larger color difference in the graining) are not as relevant for log structures.

5.1 Product Performance

5.1.1 Control

The control samples behaved much as uncoated wood is expected to behave upon exposure to the elements: it turned darker and silvered, checks of various sizes formed across the surface as the fabric was stressed, wetting of just the surface caused the samples to cup inward, and the surfaces roughened and lost cellulose fibers mostly in the earlywood due to ultraviolet radiation and abrasion. The control group lost the least amount of weight compared to the other cohorts, but this is likely because the weight loss was purely related to the wood components rather than wood loss as well as product loss. FTIR confirmed the loss of the lignin at the surface and the water repellency showed a significant drop in hydrophobicity of the surface after weathering.

5.1.2 Allbäck Boiled Organic Linseed Oil

The linseed oil treated samples retained much of their hydrophobicity through the weathering process, most likely due to the deep penetration of the product. In examination of the final cohort, the majority of the samples appeared to be in fairly good condition with a stable substrate that did not shift too far in color away from the weathered control. On average these samples lost about the same percentage of weight as the other treated samples. This treatment also has the benefit of a long history of use in the wood industry, and likely on the Bar BC Ranch, as a conditioning and water-repellent treatment and is a very ecological option. The organic boiled linseed oil from Allbäck is more expensive than the other products and has no pigmentation for ultraviolet protection. However, Allbäck's product is very high quality, low viscosity, and has a greater depth of penetration; thus, it tends to have a longer working life than most other linseed oils on the market.

5.1.3 Paraffin and Mineral Spirits

As previously mentioned, the very small amount of paraffin in the recipe utilized in this experiment appears to have had very little effect on the weathering ability of the sample. It behaved much the same as the control, the surfaces losing much of their hydrophobicity in weathering so that three could not even be measured for contact angles as well as being very close in coloring and surface appearance to the controls. Additionally, the samples lost about the same percentage of fabric as the other treatments, but since there was very little paraffin deposited in the sample, it can be inferred that a greater amount of the fabric lost was the wood itself. It is a very inexpensive treatment and environmentally-friendly when low-VOC mineral spirits are used, but the formulation must be improved in order for it to be effective as a protective treatment and water repellent. Normally paraffin is usually used in combination with linseed oil for greater penetration and water repellency, but in the case of this research, the variables were isolated in two different treatments in order to better understand their performance as single variable components.

5.1.4 DEFY Extreme Exterior Clear Wood Stain

The DEFY product made many claims about its UV protective zinc oxide nanoparticles and their density of deposition on the surface while not affecting the color of the wood. In addition to the low-VOC waterborne formula, this product offered new technology for wood preservation. Indeed, upon inspection of the treatment on a glass slide, there was a large concentration of colorless particles that were much smaller than those seen in the other treatments. The coloring of the wood barely changed upon application of the treatment, and the weathered DEFY samples on average were the closest in coloring to the weathered controls.[1] The average percent weight loss was about the same as with the other products. The lack of oil in the product base appears to have affected the conditioning of the wood, for, when compared to the oil-based products, the samples appear dry and have very roughened surfaces for the most part. However, this lack of oil does not appear to have affected the hydrophobicity, for the dense deposit of nanoparticles appears to act as a water barrier as well. The acrylic-based deterioration product detected in FTIR analysis should be explored further to determine what it is, whether it is actually a result of degradation, and what effect it might have on wood and the environment. An additional downside to this product is its relatively high cost.

5.1.5 Armstrong's Wood Stain for Decks (Natural Tone)

This product strongly advertises its mixture of drying and non-drying oils for better conditioning within the wood substrate with a protective coating at the surface. Treatment retention of the oils at least appears to be quite good, for the samples still left oil marks on any paper they came into contact with even after weathering. Additionally, the percentage of

[1] With the exception of the paraffin and mineral spirits samples which behaved much the same as the controls.

material loss for this product was the lowest of the products tested. The treated samples retained their water repellency as well. The pigmentation of the product is fairly light and more of a warm tone due to the natural iron oxide pigments; the final weathered product was within ten units of the weathered control as well. This product has low VOC and the manufacturers are very environmentally conscious from being based in California where limits are lower than in most states.

5.1.6 TWP 1500 Natural Stain (Natural Tone)

The water repellency of the TWP product was excellent both before and after weathering, in fact the weathered surfaces were more repellent than many of the pre-weathered surfaces of other products. While the treatment initially appeared very dark compared to the control and had one of the greatest color differences, it eventually weathered to be fairly close to color of the controls. Inspection of the product on a glass slide shows what appears to be two different types of particles, translucent particles as well as clumps of colored particles for pigmentation. FTIR indicated that lignin had degraded out of the surface of the TWP treated samples and also suggested the presence of a calcium-based weathering deposit on the surface, perhaps deriving from product degradation. This phenomena should be investigated further. Fabric loss was slightly higher than the average for the samples.

5.1.7 Flood CWF-UV 5 Penetrating Wood Finish for Fences, Decks, and Siding (Natural Tone (Clear))

Water repellency decreased during the weathering process, though the weathered samples are still hydrophobic. The coloring of the Flood product was much more orange-toned than that of the other products and the weathered surface was the furthest from the weathered control. Likely wood treated with this product would not fit in well with the extant fabric at the

Bar BC. Additionally, upon application, the "clear" product had a distinct orange tone and was very thick, appearing to deposit more of a film on the surface rather than penetrate deeply. The oil version of this product may be worth further investigation, but this acrylic product is not recommended for further testing on site.

5.1.8 Messmer's U.V. Plus Exterior Wood Finish (Natural)

This product and the Armstrong stain appear to be very similar in composition and performance, though in evaluations of the individual cohorts the Messmer's samples had a greater amount of samples that were ranked "poor" or "bad". The water repellent qualities of the treated samples remained about the same before and after weathering, and FTIR indicated that the surfaces retained the treatment but that most of the lignin is gone. The percentage of weight loss was about average. The final color comparisons between weathered control samples and samples treated with Messmer's showed that the difference was quite large, though this product may better compared to the dark weathered logs found on many sites in Grand Teton National Park.

5.2 Summary of Results

After a full review of the treatments, it was apparent that each had strengths and weaknesses in terms of the different properties used for evaluation. A summary of these differences can be found in the following table (table 19) where each product was ranked on a scale from 1 – 10, where 1 is bad and 10 is excellent.

	Physical Degradation of Surface (Microscopic Inspection)	Treatment Absorbed (Weight Change)	Material Lost During Weathering (Weight Change)	Color Change - Final Result to Control (Spectroph-otometer)	Lignin Degradation at Surface (FTIR)	Water Repellence (Contact Angle Measurement)	Treatment Retention (FTIR)
Control	2	n/a	5	n/a	1	2	n/a
Linseed Oil	8	9	4	6	2	9	7
Paraffin and Mineral Spirits	2	1	5	8	1	2	1
DEFY Extreme	5	8	7	9	5	7	7
Armstrong's Wood Stain (Natural)	7	10	9	9	4	8	9
TWP 1500 Series (Natural)	8	5	4	6	3	10	8
Flood CWF UV-5 (Clear)	4	3	6	2	2	5	4
Messmer's UV Plus (Natural)	6	7	5	4	5	8	9

Table 19. Comparison of Treatments in terms of Testing Properties.

In accordance with this table, the treatments can be ranked by their overall performance in accelerated weathering as follows (from highest ranking to lowest):

Armstrong’s Wood Stain (Natural)

DEFY Extreme Exterior Clear Wood Stain

Messmer’s UV Plus (Natural)

TWP 1500 Series (Natural)

Linseed Oil

Flood CWF UV-5 (Clear)

Paraffin and Mineral Spirits

Further testing is necessary to confirm these results in the field.

Chapter 6: Recommendations

Further field testing is recommended for those products that performed the best during accelerated weathering. In accordance with the rankings on product performance established in the conclusions section, these products are Armstrong's Wood Stain (Natural), DEFY Extreme Exterior Clear Wood Stain, Messmer's UV Plus (Natural), and TWP 1500 Series (Natural). Additional recommendations for further treatment evaluation includes the combination of the traditional treatments used in this experiment. Many traditional treatment recipes published in the last century recommend mixing paraffin wax, linseed oil, mineral spirits or turpentine, and varnish for color. While this research served to isolate two of these variables to see their performance, a further treatment of the above mixture should be tested for performance in the lab and the field.

6.1 Suggestions for Further Testing

6.1.1 Natural Weathering

Many of the considerations listed in the conclusions will be addressed in subsequent natural weathering testing this summer on site at the Bar BC Dude Ranch.[1] In natural outdoor weathering, wood is affected by a complex combination of chemical, mechanical, and light energies that depend on the local climactic conditions as well as the duration and severity of exposure to the sun and rain. In most cases, the conditions of natural weathering are much less aggressive than those seen in accelerated weathering. Cycles of wetting and drying are less intense, temperatures vary, and the ultraviolet radiation of the sun is not of the same intensity

[1] June – August, 2015.

as the UV-B bulbs. Thus, follow up testing on similar samples with these products is extremely necessary to truly understand their working potential for protecting wood surfaces.

Additionally, as previously mentioned, full logs of both new and weathered material will be available for testing to see how they accept treatments and subsequently weather on both tangential and transverse orientations. Therefore the aesthetics of treatment for both states of material can be designed to approach the same basic result while still trying to retain as much original fabric as possible.

6.1.2 Accelerated Weathering

Further accelerated weathering testing could be used to explore many other aspects of the treatment concerns that were not addressed in this thesis. First of all, only seven treatments, two historic and five commercial, were tested in this research. As can be inferred from the table generated in product selection[2], an incredibly large collection of wood treatments are available from a wide variety of manufacturers today. Those appropriate for conservation limits the pool slightly, but there still remains a plethora of new treatments to explore and compare via accelerated and natural weathering. This is especially relevant in the rapidly developing low-VOC coating industry.

Additionally, already weathered material could be inserted into the machine to test the performance of treatments on these historic samples as well to see how they would further weather and whether the treatments provided enough consolidation and protection for the historic wood in extreme circumstances. This could also provide the opportunity to see how the penetrating treatments are affected by a previously treated wood substrate, especially if the previous treatment was oil based while the new treatment is water-based. Rounded samples

[2] Found in Appendix A.

with bark still on them or with the bark pried off could also give better insight into how the new logs inserted for repairs weather with no cutting or sanding preparation before treatment.

The effects of weathering and treatments on different grain orientations could also be explored as well as experimenting with the effects of different cycle sets in the Weatherometer on similar wood samples. More intricate cycles for material weathering have been explored in recent years and may have very different, and possibly more natural, weathering results. Additionally, conditions in the machine could be manipulated to more closely resemble the climate of Grand Teton National Park. Condensation cycles could be limited or even eliminated and UV cycles extended. These cycles could also be manipulated to better understand the effects of each degradation mechanism on the lodgepole pine samples in an effort to better correlate certain kinds of damage to each mechanism.

In order to better determine treatment retention and the decay of wood fabric, future testing should include Scanning Electron Microscopy (SEM) if time and resources allow. SEM can allow for surface mapping to both detect lignin and cellulose degradation as well as detect protective particles deposited during treatment and whether they still remain on the wood surface after weathering.

Bibliography

Allen, Norman S., Michele Edge, Amaya Ortega, Christopher M. Liauw, John Stratton, and Robert B. McIntyre. "Behaviour of Nanoparticle (Ultrafine) Titanium Dioxide Pigments and Stabilisers on the Photooxidative Stability of Water Based Acrylic and Isocyanate Based Acrylic Coatings." *Polymer Degradation and Stability* 78, no. 3 (June 2002), 467-478.

Allen, Norman S., Michele Edge, Amaya Ortega, Gonzalo Sandoval, Christopher M. Liauw, Joanna Verran, John Stratton, and Robert B. McIntyre. "Degradation and Stabilisation of Polymers and Coatings: Nano versus Pigmentary Titania Particles." *Polymer Degradation and Stability 85*, no. 3 (2004), 927-946.

Allen, Norman S., Michele Edge, Gonzalo Sandoval, Amaya Ortega, Christopher M. Liauw, John Stratton, and Robert B. McIntyre. "Interrelationship of Sectroscopic Properties with the Thermal and Photochemical Behaviour of Titanium Dioxide Pigments in Metallocene Polyethylene and Alkyd Based Paint Films: Micron Versus Nanoparticles." *Polymer Degradation and Stability* 76, no. 2 (2002), 305-319.

Aloui F., A. Ahajji, Y. Irmouli, B. George, B. Charrier, A. Merlin. "Inorganic UV Absorbers for the Photostablisation of Wood-Clearcoating systems: Comparison with Organic UV Absorbers." *Applied Surface Science 253* (2007), 3,737-3,745.

Anderson, Erin L., Zenon Pawlak, Noel L. Owen, and William C. Feist. "Infrared studies of wood weathering. Part I: Softwoods." *Applied Spectroscopy* 45, no. 4 (1991): 641-647.

Anderson, Erin L., Zenon Pawlak, Noel L. Owen, and William C. Feist. "Infrared studies of wood weathering. Part II: Hardwoods." *Applied Spectroscopy* 45, no. 4 (1991): 648-652.

"Beautiful, Easy Stain." *Flood.com*. Web. 21 Jan. 2015. <http://www.flood.com/wood-care-solutions/product/3/details>.

Beckman, Christine L. *Evaluating the Displacement Modes and Associated Risks of Stacked Log Structures*. Thesis. University of Pennsylvania, 2013.

Black, John M., Don F. Laughnan, and Edward A. Mraz. *Forest Products Laboratory Natural Finish*. No. FSRN-FPL-046-REV. Forest Products Lab: Madison, WI, 1979.

Blackburn, S.R., B.J. Meldrum, and J. Clayton. “The Use of Fine Particle Titanium Dioxide for UV Protection in Wood Finishes.” *Faerg och Lack Scandinavia 37*, no. 9 (1991), 192–196.

Blanchard, Vincent, and Pierre Blanchet. "Color Stability for Wood Products During Use: Effects of Inorganic Nanoparticles." *BioResources* 6, no. 2 (2011), 1219-1229.

Borgin, K. “The Protection of Wood against Dimensional Instability.” *Forestry in South Africa*. Vol. 9 (1968), 81–94.

Bulian, Franco, and Jon Graystone. *Wood Coatings: Theory and Practice*. Elsevier, 2009.

Cantu, Richard Jason. *Green Roofs for Historic Buildings: Case Study of the Bar BC Dude Ranch at Grand Teton National Park*. Thesis. University of Pennsylvania, 2012.

Chang, S.-T., D.N.-S. Hon, W.C. Feist. “Photodegradation and Photoprotection of Wood Surfaces." *Wood and Fiber 14*, no. 2 (1982), 104-117.

Clausen, Carol A. "Enhancing durability of wood-based composites with nanotechnology.” *Nanocelluloses* (2012).

Clausen, Carol A., Frederick Green III, and S. Nami Kartal. "Weatherability and leach resistance of wood impregnated with nano-zinc oxide." *Nanoscale Res Lett* 5, no. 9 (2010), 1464-1467.

Clausen, Carol A. "Innovations in Wood Protection in the age of Nanotechnology." In *Series: Conference Proceedings*. 2014.

Clausen, Carol A., Vina W. Yang, Rachel A. Arango, Federick Green III, Frederick Green III, Rachel A. Arango, and Stan T. Lebow. "Feasibility of nanozinc oxide as a wood preservative." *Proc Am Wood Protect Assoc* 105 (2009), 255-260.

Cristea, Mirela Vlad, Bernard Riedl, and Pierre Blanchet. "Effect of addition of nanosized UV absorbers on the physico-mechanical and thermal properties of an exterior waterborne stain for wood." *Progress in Organic Coatings* 72, no. 4 (2011): 755-762.

de Meijer, Mari. "Review on the durability of exterior wood coatings with reduced VOC-content." *Progress in Organic Coatings* 43, no. 4 (2001): 217-225.

"DEFY Extreme Wood Stain - DEFY Exterior Wood Stain." DEFY Wood Stain. Web. 20 Jan. 2015. <http://www.defywoodstain.com/products/wood-stains/defy-extreme-wood-stain/>.

Dhoke, Shailesh K., A. S. Khanna, and T. Sinha. "Effect of nano-ZnO particles on the corrosion behavior of alkyd-based waterborne coatings." *Progress in Organic Coatings* 64, no. 4 (2009), 371-382.

Doubledee, Benjamin Allen. *A Design Feasibility Study for the Preservation of the Main Cabin at the Bar BC Dude Ranch, Grand Teton National Park, Wyoming*. Thesis. University of Pennsylvania, 2014.

Eastman, Whitney. "Uses of the Products of the Flax Plant." The History of the Linseed Oil Industry in the United States. Minneapolis: T.S. Denison, 1968.

Egenberg, Inger Marie, John A.b. Aasen, Ann Katrin Holtekjølen, and Elsa Lundanes. "Characterisation of Traditionally Kiln Produced Pine Tar by Gas Chromatography-mass Spectrometry." *Journal of Analytical and Applied Pyrolysis*: 143-55.

Egenberg, Inger Marie. *Tarring Maintenance of Norwegian Medieval Stave Churches: Characterisation of Pine Tar During Kiln-Production, Experimental Coating Procedures and Weathering*. Acta Universitatis Gothoburgensis, 2003.

Evans, Philip D. “Weathering and Photoprotection of Wood.” In *Development of Commercial Wood Preservatives: Efficacy, Environmental, and Health Issues*, edited by Tor P. Schultz, Holger Militz, Michael H. Freeman., Barry Goodell, and Darrel D. Nicholas, 69-117. Vol. 982 of An American Chemical Society Publication, 2008.

Feist, William C. *Replacement Wooden Frames and Sash: Protecting Woodwork against Decay*. Washington, D.C.: U.S. Dept. of the Interior, National Park Service, 1984.

Feist, William C. "Weathering performance of painted wood pretreated with water-repellent preservatives." *Forest Products Journal* 40, no. 7/8 (1990): 21-26.

Flexner, Bob. *Understanding wood finishing*. Rodale Press, 1996.

"Fourier Transform Infrared Spectroscopy (FTIR)." *Fourier Transform Infrared Spectroscopy*. Web. 20 Nov. 2014. <http://www.mee-inc.com/hamm/fourier-transform-infrared-spectroscopy-ftir/>.

George, Béatrice, Ed Suttie, André Merlin, and Xavier Deglise. "Photodegradation and photostabilisation of wood–the state of the art." Polymer Degradation and Stability 88, no. 2 (2005), 268-274.

Golton, William C. *Analysis of Paints and Related Materials Current Techniques for Solving Coatings Problems*. Philadelphia, PA: ASTM, 1992.

Gorman, Thomas M., and William C. Feist. "Chronicle of 65 years of wood finishing research at the Forest Products Laboratory." (1989).

Graham, Roy Eugene, and Associates. 1993. “Bar BC Dude Ranch: Grand Teton National Park, Wyoming.” Historic Structures Report. U.S. Department of the Interior, National Park Service, Rocky Mountain Regional Office.

Graystone, Jon, and I. L. Abrahams. "Natural weathering of exterior wood coatings: a comparison of performance at five European sites." *European Coatings Journal* 10 (1996): 706-711.

Hocken, J., K. Pipplies, K. Schulte. "The Advantageous Use of Ultra-Fine Titanium Dioxide in Wood Coatings, Creative Advances in Coatings Technology" in Proceedings of the Fifth Nuremberg Congress, Nuremberg (Nuremberg), Germany, April 2–14, 1999.

Hoeflaak, M., and W. F. Gard. "Test methods for a reliable assessment of water-borne paints for exterior wood protection." *Surface Coatings International* Part B: Coatings Transactions 84, no. 4 (2001): 259-262.

Hon, David N.-S. “Weathering and Photochemistry of Wood” in *Wood and Cellulosic Chemistry, Revised, and Expanded* edited by David N-S. Hon and Nobuo Shiraishi, 513-546. CRC Press, 2000.

Kishino, Masanori, and Takato Nakano. "Artificial weathering of tropical woods. Part 1: Changes in wettability." *Holzforschung* 58, no. 5 (2004): 552-557.

Kishino, Masanori, and Takato Nakano. "Artificial weathering of tropical woods. Part 2: Color change." *Holzforschung* 58, no. 5 (2004): 558-565.

Knaebe, Mark. "Alternatives to the Madison Formula, the Original Do-It-Yourself Semitransparent Stain." Madison, WI: Forest Products Laboratory, 2002.

Lamour, Guillaume, et al. "Contact Angle Measurements Using a Simplified Experimental Setup." *Journal of Chemical Education* 87.12 (2010): 1403-1407.

"Linolja Kokt, Avslemmad 1L." - *Allbäck Linoljeprodukter AB*. Web. 13 Jan. 2015. <http://linoljeprodukter.se/shop/product/linolja-kokt-avslemmad-1l?tm=webshop/linolja>.

Lionetto, Francesca, Roberta Del Sole, Donato Cannoletta, Giuseppe Vasapollo, and Alfonso Maffezzoli. "Monitoring Wood Degradation during Weathering by Cellulose Crystallinity." *Materials* (2012): 1910-922.

Lowry, Michael S., David R. Hubble, Amy L. Wressell, Menas S. Vratsanos, Frank R. Pepe, and Charles R. Hegedus. "Assessment of UV-permeability in nano-ZnO filled coatings via high throughput experimentation." *Journal of Coatings Technology and Research* 5, no. 2 (2008): 233-239.

Macleod, I.T., A.D. Scully, K.P. Ghiggino, P.J.A. Ritchie, O.M. Paravagna, and B. Leary. "Photodegradation at the Wood-Clearcoat interface." *Wood Science and Technology 29*, no. 3 (1995), 183-189.

Mahltig, B., H. Böttcher, K. Rauch, U. Dieckmann, R. Nitsche, and T. Fritz. "Optimized UV protecting coatings by combination of organic and inorganic UV absorbers." *Thin Solid Films* 485, no. 1 (2005), 108-114.

McCaig, Iain, and Brian Ridout, eds. *Practical Building Conservation: Timber*. Burlington, VT: Ashgate Publishing, Ltd., 2012.

"Messmer's UV Plus – Deck Stain, Wood Stain." *RSS*. Web. 20 Jan. 2015. <http://www.messmers.com/messmers-uv-plus-deck-stain>.

Miniutti, V.P. "Microscopic Effects of Ultraviolet Irradiation and Weathering on Redwood Surfaces and Clear Coatings. *Journal of Paint Technology 4*, no. 531 (1967), 275-284.

Miniutti, Victor P. *Microscopic Observations of Ultraviolet Irradiated and Weathered Softwood Surfaces and Clear Coatings*. Forest Products Laboratory, 1967.

Miniutti, V.P. "Reflected-Light and Scanning Electron Microscopy of Ultraviolet Irradiated Redwood Surfaces." *Microscope 1*, no. 8 (1970), 61 -72.

"Oil Based Wood Stain: Transparent Colors." - *Armstrong-Clark Co. Site*. Web. 18 Jan. 2015. <http://www.armclark.com/oil-based-wood-stains-and-products/transparent-oil-based-wood-stain.html>.

Pinnell, Sheldon R., David Fairhurst, Robert Gillies, Mark A. Mitchnick, and Nikiforos Kollias. "Microfine zinc oxide is a superior sunscreen ingredient to microfine titanium dioxide." *Dermatologic Surgery* 26, no. 4 (2000), 309-314.

"Preparing A Non-Toxic Water-Repellent Preservative." *U.S. General Services Administration*, n.d. Web. 20 Jan. 2015. <http://www.gsa.gov/portal/content/113086>.

Proniewicz, Leonard M, Czesława Paluszkiewicz, Aleksandra Wesełucha-Birczyńska, Andrzej Barański, and Dorota Dutka. "FT-IR and FT-Raman Study of

Hydrothermally Degraded Groundwood Containing Paper." *Journal of Molecular Structure* (2002): 345-53.

"QUV Accelerated Weathering Tester || Q-Lab." *QUV Accelerated Weathering Tester || Q-Lab*. Web. 15 Oct. 2014. <http://www.q-lab.com/products/quv-weathering-tester/quv/>.

QUV Accelerated Weathering Tester with Solar Eye Irradiance Control & Spray Option, Model: QUV/SE/SO, Operating Manual. Cleveland: Q-Panel, 1993.

Ridout, Brian. *Timber Decay in Buildings: The Conservation Approach to Treatment.* New York: Routledge, 2000.

Rowell, Roger M. *Handbook of Wood Chemistry and Wood Composites*. Boca Raton, FL: CRC, 2005.

Salla, Jayashree, Krishna K. Pandey, and Kavyashree Srinivas. "Improvement of UV resistance of wood surfaces by using ZnO nanoparticles." *Polymer Degradation and Stability* 97, no. 4 (2012): 592-596.

Schmalzl, K.j., and P.d. Evans. "Wood Surface Protection with Some Titanium, Zirconium and Manganese Compounds." *Polymer Degradation and Stability* (2003): 409-19.

Schulte, K. "Application of Micronized Titanium Dioxide as Inorganic UV Absorber." In *11th Asia Pacific Coatings Conference*. 2001.

Sharrock, R.F. “A European Approach to UV Protection with a Novel Pigment.” *J. Coat. Tech. 62* (1990), 125-130.

Singh, A.P and B.S.W. Dawson. “The Mechanism of Failure of Clear Coated Wooden Boards as Revealed by Microscopy.” *IAWA J. 24* (2003), 1-11.

Sun, Qingfeng, Yun Lu, Haimin Zhang, Huijun Zhao, Haipeng Yu, Jiasheng Xu, Yanchun Fu, Dongjiang Yang, and Yixing Liu. "Hydrothermal fabrication of rutile TiO< sub> 2</sub> submicrospheres on wood surface: An efficient method to prepare UV-protective wood." *Materials Chemistry and Physics* 133, no. 1 (2012), 253-258.

Tshabalala, Mandla A. and Li-Piin Sung. "Wood surface modification by in-situ sol-gel deposition of hybrid inorganic–organic thin films." *Journal of Coatings Technology and Research* 4, no. 4 (2007), 483-490.

"TWP 1500 Stain." *TWP 1500 Stain*. Web. 20 Jan. 2015. <http://www.twpstain.org/twp-1500-stain.html>.

United States. National Park Service. "Park Statistics." *National Parks Service*. U.S. Department of the Interior, 4 Apr. 2015. Web. 25 Mar. 2015. <http://www.nps.gov/grte/learn/management/statistics.htm>.

United States. National Park Service. "Weather." *National Parks Service*. U.S. Department of the Interior, 4 Apr. 2015. Web. 25 Mar. 2015. <http://www.nps.gov/grte/planyourvisit/weather.htm>.

Vignolo, Carlos E. "Some Applications of Ultrafine TiO2." *European Coatings Journal 5* (1995), 359-361.

Vlad-Cristea, Mirela, Bernard Riedl, Pierre Blanchet, and Emilio Jimenez-Pique. "Nanocharacterization techniques for investigating the durability of wood coatings." *European Polymer Journal* 48, no. 3 (2012): 441-453.

Williams, R. Sam, and William C. Feist. "Water repellents and water-repellent preservatives for wood." (1999).

Williams, R. Sam. "Effect of grafted UV stabilizers on wood surface erosion and clear coating performance." *Journal of Applied Polymer Science* 28, no. 6 (1983), 2093-2103.

Williams, R. Sam, Peter Sotos, and William C. Feist. "Evaluation of several finishes on severely weathered wood." *Journal of Coatings Technology* 71, no. 895 (1999): 97-102.

Williams, R. Sam. "Weathering of Wood." In *Handbook of Wood Chemistry and Wood Composites* edited by Roger M. Rowell. CRC press, 2012.

Woodward, Roger P. "Contact Angle Measurements Using the Drop Shape Method." *First Ten Angstroms Inc., Portsmouth, VA* (1999).

Wypych, George. *Handbook of Material Weathering* Fifth Edition. Toronto: ChemTec Publishing, 2013.

Wypych, George. *Handbook of Material Weathering*. 4th ed. Toronto: ChemTec Pub., 2008.

ASTM Standards

ASTM Book of Standards Volume 06.01. West Conshohocken PA: ASTM International, 2011. s.v. "**ASTM D2244 – 15** Standard Practice for Calculation of Color Tolerances and Color Differences from Instrumentally Measured Color Coordinates."

ASTM Book of Standards Volume 06.01. West Conshohocken PA: ASTM International, 2011. s.v. "**ASTM D3924 – 80(2011)** Standard Specification for Standard Environment for Conditioning and Testing Paint, Varnish, Lacquer, and Related Materials."

ASTM Book of Standards Volume 06.01. West Conshohocken PA: ASTM International, 2011. s.v. "**ASTM D4585/D4585M – 13** Standard Practice for Testing Water Resistance of Coatings Using Controlled Condensation."

ASTM Book of Standards Volume 06.01. West Conshohocken PA: ASTM International, 2011. s.v. "**ASTM D4587 – 11** Standard Practice for Fluorescent UV-Condensation Exposures of Paint and Related Coatings."

ASTM Book of Standards Volume 06.02. West Conshohocken PA: ASTM International, 2011. s.v. "**ASTM D6763 - 08(2014)** Standard Guide for Testing Exterior Wood Stains and Clear Water Repellents."

ASTM Book of Standards Volume 06.02. West Conshohocken PA: ASTM International, 2011. s.v. "**ASTM D7787/D7787M – 13** Standard Practice for Selecting Wood Substrates for Weathering Evaluations of Architectural Coatings."

ASTM Book of Standards Volume 14.04. West Conshohocken PA: ASTM International, 2011. s.v. "**ASTM G113 – 14** Standard Terminology Relating to Natural and Artificial Weathering Tests of Nonmetallic Materials."

ASTM Book of Standards Volume 14.04. West Conshohocken PA: ASTM International, 2011. s.v. "**ASTM G147 – 09** Standard Practice for Conditioning and Handling of Nonmetallic Materials for Natural and Artificial Weathering Tests."

ASTM Book of Standards Volume 14.04. West Conshohocken PA: ASTM International, 2011. s.v. "**ASTM G151 – 10** Standard Practice for Exposing Nonmetallic Materials in Accelerated Test Devices that Use Laboratory Light Sources."

ASTM Book of Standards Volume 14.04. West Conshohocken PA: ASTM International, 2011. s.v. "**ASTM G154 – 12a** Standard Practice for Operating Fluorescent Ultraviolet (UV) Lamp Apparatus for Exposure of Nonmetallic Materials."

ASTM Book of Standards Volume 14.04. West Conshohocken PA: ASTM International, 2011. s.v. “**ASTM G156 – 09** Standard Practice for Selecting and Characterizing Weathering Reference Materials.”

ASTM Book of Standards Volume 14.04. West Conshohocken PA: ASTM International, 2011. s.v. “**ASTM G169 – 01(2013)** Standard Guide for Application of Basic Statistical Methods to Weathering Tests.”

Appendix A – Treatment Information

Instructions for correct application of the chosen penetrating coatings derived from both product packaging as well as the manufacturers' websites. The recipe for paraffin with mineral spirits came from an old Park Service recipe that can be found from a variety of sources, including publications by the staff of the Forest Products Laboratory of the US Department of Agriculture as well as in many articles on non-toxic, hydrophobic treatments for wood.

Allbäck Boiled Organic Linseed Oil

Instructions for application on the product label:

> This Boiled Maintenance Oil is a refined purified and sterilized Swedish linseed oil. The oil is used as wood preserver and primer. The oil is easy to apply with a sponge. The surface should be clean and dry. Use infrared heat on the oil, thereby helping it to penetrate into the wood. The oil can also be used to dilute the Allbäck linseed paint if necessary.

Paraffin and Mineral Spirits

As previously mentioned, a number of recipes exist for paraffin-based hydrophobic treatments in both published sources as well as in wood treatment forums[1] that have different ratios of constituents. I focused on the proportion of a water-repellent formulation disseminated by Forest Products Laboratory (Feist, 1984).

Instructions for formulation:

> "The water-repellent treatment is easily done before or after construction and before painting. A simple formula, easily prepared is:

- Exterior varnish – 3 cups

[1] These forums are generally concerned with homemade non-toxic wood treatment recipes that can used on wooden elements that come into contact with food sources, such as boxes and posts for retaining gardens, cutting boards, tables, etc.

- Paraffin wax – 1 ounce
- Mineral Spirits, or paint thinner, or turpentine – Add to make 1 gallon

> Treatment is best done by dipping the wood for 1 to 3 minutes in the solution. If dipping is inconvenient, liberal brush application can be made - paying particular attention to heavy treatment of all board ends and joints. The treated surface can be painted after 2 or 3 days of warm weather. In fact, paint should last longer over the treated surface than over untreated wood."

In an effort to see how just paraffin would affect the preservation of the wood, I eliminated the varnish component and accounted for the volume loss in calculations. The recipe makes one gallon of treatment, a volume too large for practicality in this experiment, so it was reduced by 75% so that the treatment could be mixed in a beaker. 0.39 g of paraffin was melted in a beaker in a hot water bath on a hot plate and 760 mL of mineral spirits added and mixed. The mixture was cooled slightly but kept warm for application to the wood surface.

DEFY Extreme Exterior Clear Wood Stain

Instructions for application on the product label:

Surface Preparation:

1. Strip – Do not use DEFY Extreme Exterior Clear Wood Stain over painted or varnished surfaces. These surfaces must be stripped prior to application of the product.
2. Clean – Wood surfaces must be clean, porous, and dry before applying DEFY Extreme Exterior Clear Wood Stain. Use DEFY Wood Cleaner to remove mill glaze, mildew, graying and other foreign matter that might block surface pores and interfere with product penetration. Rinse thoroughly with garden hose or power washer (maximum 1200 p.s.i.). DEFY Wood Cleaner will darken redwood and some types of cedar; however, this darkening will disappear once the wood is treated with DEFY Wood Brightener.
3. Brighten – While surface is still wet from cleaning, sue DEFY Wood Brightener to neutralize the wood, restore the wood to its natural color, and open the pores of the wood, allowing the stain to be more easily absorbed.

Application:

1. Weather Conditions – Surface and air temperatures should be between 45˚ F and 95˚ F. Avoid application in direct sunlight. Although surface may be slightly damp, do not apply to wet or water saturated surfaces, or when rain is expected within 12 hours.

2. Water Test – After allowing the wood to thoroughly dry from cleaning and brightening, sprinkle a few drops of water on the wood. It should soak in within a few seconds. If it doesn't, then don't apply the finish. The wood is either not dry enough or not porous enough to accept the finish correctly. Test a small area before starting general application to assure desired results.
3. Mix Well – Shake or stir contents before and periodically during use. Do not thin product.
4. Protect Adjacent Areas – Use plastic, cardboard, and/or drop cloths to protect all adjacent non-targeted surfaces such as siding, windows, masonry, plant life, etc. from overspray and runoff. Immediately remove overspray from non-targeted areas with soap and water. Overspray that is allowed to dry will be difficult to remove; dried product cannot be removed from concrete and masonry.
5. Use the Right Equipment – Hand brushed should be high quality nylon or polyester. A pad applicator or deck brush may also be sued. For large areas a pump-up or an airless sprayer may be used. If using an airless sprayer, use tips between 0.011 and 0.015, and use the lowest pressure that achieves a uniform spray pattern to minimize fogging and overspray. When spraying, always back brush to ensure a uniform application, and to break the surface tension of the wood so the stain will penetrate deeper and last longer.
6. Decks – Start by applying DEFY Extreme Exterior Clear Wood Stain to the railings, benches, and undersides of upper level decks (only one coat is required on undersides). Once underside is treated, immediately brush out all overspray, drips, etc. on top of deck. Treat horizontal surfaces last.
7. Horizontal Surfaces – On horizontal cedar, mahogany, and other dense woods, apply only one coat of finish. For pressure treated lumber and other porous woods apply two coats, waiting approximately 20 minutes between coats. It is very important to not let the first coat dry completely before applying the second coat. Brush product into surface working out all drips, puddles, or areas of overspray before product dries. Do not over apply finish. To avoid the possibility of peeling, apply only as much finish as the wood can easily absorb. A sure indication of over application is a shiny appearance. Complete entire sections or to a natural break before allowing to dry. Never break in the middle of a board. Thoroughly coat the ends of boards or logs to prevent water penetration. All surface checks on logs should be thoroughly coated.
8. Vertical Surfaces – Start from the bottom and work up. Treat the entire length of a board before moving up. IF necessary, brush or feather in to avoid lap marks. Brush in product before it dries and work out drips, runs, or overspray.
9. Wood Shingles – Clean and test for porosity. Apply two, heavy saturation coats. Depending on porosity, a third coat may be necessary to achieve total saturation. Back brush between coats to ensure a uniform application. Brush out all drips and puddles. To avoid restart lines, start at the bottom and treat entire length before moving up.

10. Dry Time – To touch, 2 to 6 hours depending on temperature and humidity. Allow 24 hours for deck to completely cure before using.
11. Clean up – Clean tools and equipment immediately after each use with soap and water.
12. Coverage – With two coats, one gallon of DEFY Extreme Exterior Clear Wood Stain will cover approximately 100 – 150 sq. ft., depending on wood texture and porosity.

Armstrong's Wood Stain for Decks (Natural Tone)

Instructions for application on the product label:

1. Use – For all new, old, and pressure treated unpainted wood surfaces such as: decks, siding, shakes and shingles, fences and log homes where color retention, water repellency and wood conditioning is the desired goal.
2. Surface Preparation – Surface must be clean, dry and free of dust and dirt. Wash surface suing a mixture of soap, chlorinated bleach and water with mild scrubbing. Rinse throughout and/or pressure wash. Previously stained surfaces should be tested with Armstrong;s Wood Stain prior to entire application to ensure penetration and finish appearance.
3. Application Instructions – Easy application by brush, roller, garden sprayer or airless spray equipment. Back brushing or back rolling recommended with spray applications. Should the first coat absorb within 30-60 minutes, a second coat can be applied overnight. If there are any wet spots after 24 hours, remove them with a dry towel. See rag disposal cautions on the can label. Reapply at 2 to 4 year intervals for vertical surfaces and 1 to 3 year intervals for horizontal surfaces, depending upon weather exposure. Life expectancy on hardwoods is 6 to 12 months.
4. Clean Up – Clean all equipment with paint thinner. All empty cans must be air dried. Dispose according to state and local regulations.

TWP 1500 Natural Stain (Natural Tone)

Instructions for application from the small sample sent in the mail:

1. Shake well prior to applying.
2. Test colors on inconspicuous area of your wooden structure.
3. For best results make sure wood is cleaned and brightened.
4. Let dry for 4-6 hours to see final color.
5. Please understand that final color of stain will depend on preparation, age of wood, application method and amount of coat(s) applied. We do not guarantee a final color.

Instructions for application from Total Wood Preservation's website on the 1500 Series Stain (How To Apply TWP 1500 Stain, http://www.twpstainhelp.com/how-to-apply-twp-1500-stain/):

1. First measure your wood surface to determine the square footage. TWP 1500 Series Wood and Deck Preservative covers approximately 150-300 sq. ft. per gallon. Buy a little more stain than you need just to be sure you do not run out at the end of the project.
2. Prior to using TWP 1500 Deck Stain, clean the wood using a brush or pressure washer along with a quality wood cleaner. Preparing the wood properly will ensure your new TWP Wood Stain will perform optimally.
3. Once the wood surface is cleaned it must dry for a minimum of 48 hours before stain can be applied. Be sure the temperature is at least 50 degrees and that dry weather is forecasted for the next several days.
4. Remove any leaves or debris that may have collected while the wood was drying. Wear protective gear like rubber gloves and safety glasses while completing your wood staining project. Thoroughly mix the TWP 1500 Wood Preservative using a paint stick until it is well blended. Be sure there are no clumps at the bottom of the pail. If the TWP stain has been sitting for some time, a paint store can shake it up for you.
5. Use plastic to protect any windows, landscaping, concrete, or siding that you do not want to stain. Begin staining the higher areas first. On wood siding, gazebos, wood shakes, and play sets start at the top and stain your way down. On wood decks it is best to start with the railings and save the deck floor for last.
6. TWP 1500 Series can be applied several ways. Use a brush, roller, stain pad, or pump sprayer to apply. With TWP 1500, the first coat is a saturation coat. It should soak in fairly quickly with the exception of new wood which may take longer. If the wood absorbs the first coat with no problem a second coat of TWP 1500 Stain may be applied. The more stain that is absorbed the better. Apply a second "wet on wet" coat within 30 minutes of the first coat.
7. Be wary of over application of the stain. If you see puddles or drips of excess stain that isn't absorbing into the wood, wipe them away using a brush or stain rag. Do not stop staining in the middle of a board. Doing so can leave lap marks. Finish each board from end to end once you begin staining.
8. TWP 1500 Series Wood and Deck Preservative is the only wood preservative registered by the EPA. It is designed for all exterior wood surfaces. It has outstanding penetration properties and excellent UV resistance from wood graying. It has superb color retention and is not prone to cracking, peeling, or flaking. TWP 1500 Series will only fade in time and can simply be cleaned and reapplied as necessary for maintenance.

Flood CWF UV-5 Penetrating Wood Finish for Fences, Decks, and Siding (Natural Tone (Clear))

Instructions for application on the product label:

Where to Use:

- For exterior use only.
- All new or weathered exterior wood that is porous enough to accept a penetrating finish.
- Exterior decks, fences, siding and furniture.

Surface Preparation:

1. Proper surface preparation is essential for the limited warranty to apply – see side of label for limited warranty details.
2. Test wood for absorbency by sprinkling water on the surface – if water is absorbed within a couple of minutes, the surface is ready for finishing. If water is not absorbed, wait 30 day and re-test.
3. Surfaces must be clean, free of dirt, grime, mildew and previous coatings.
4. Weathered, uncoated surfaces: clean with FLOOD Wood Cleaner.
5. Previously coated surfaces: remove finish with FLOOD Wood Stripper.
6. Allow wood to dry 48 hours before finishing.

Application:

1. Stir before and periodically during application.
2. Do not thin. Test color in small area.
3. Do not apply in hot sunlight or if cold, wet weather is expected within 48 hours.
4. Apply between 50˚ F (10˚ C) - 80˚ F (27˚ C).
5. Apply with synthetic brush or roller – backbrush if rolled.
6. If the first coat is absorbed within 20 minutes, apply a second coat before the first coat has dried.

Coverage:

- 150 – 250 sq ft/gal (13.9 – 23.2 sq m/gal) – coverage will vary depending on temperature and humidity.

Dry Time:

- 24 – 48 hours, depending on temperature and humidity.

Cleanup and Storage:

- Soap and water.
- Keep from freezing.

Messmer's U.V. Plus Exterior Wood Finish (Natural)

Instructions for application on the product label:

Application:

1. Prep – Make sure surface is clean, dry & in good condition. Clean weathered wood with Messmer's WD Wood & Deck Renewer. Remove previous stain or paint completely before applying UV Plus.
2. Mix – Do not thin. Stir well initially and during use. Intermix all containers of the same color to ensure uniform appearance. Cover plants, grass and concrete to protect from spills or overspray. Surface and air temperature must be between 40-95˚ F.
3. Test – Apply to a small test area to ensure complete penetration and color satisfaction before proceeding with the entire project.
4. Equip – Apply with a quality bristle brush, roller, pad, or airless sprayer. Back brush or back roll if applied by spray.
5. Apply – Apply a uniform, even coat. Stain the full length of boards, keeping a wet edge. One coat is sufficient for most applications. Excess product not

absorbed within 30-45 minutes must be removed to prevent tackiness and surface sheen.

6. Clean – Clean application equipment with mineral spirits. Close container when not in use.

Coverage:

- Different woods vary dramatically in the amount of product they can absorb. Approximate coverages are one gallon to:
    - 100 sq. ft – logs, shingles, & shakes
    - 100-125 sq. ft. – rough sawn or weathered wood
    - 150-200 sq. ft. – siding & new decks

Appendix B - Microscopic Analysis of Surfaces and Treatments

Surface Inspection with Leica MZ16a Microscope and photographs taken with a Nikon DS Fi-1 Camera with NIS Elements BR Software

Control:

1x Magnification

Control 1, Pre-Weathering

Control 1, Post-Weathering

Control 2, Pre-Weathering

Control 2, Post-Weathering

Control 3, Pre-Weathering

Control 3, Post-Weathering

Surface Inspection with Leica MZ16a Microscope and photographs taken with a Nikon DS Fi-1 Camera with NIS Elements BR Software

Control:

1x Magnification

Control 4, Pre-Weathering

Control 4, Post-Weathering

Control 5, Pre-Weathering

Control 5, Post-Weathering

Control 6, Pre-Weathering

Control 6, Post-Weathering

Surface Inspection with Leica MZ16a Microscope and photographs taken with a Nikon DS Fi-1 Camera with NIS Elements BR Software

Control:

10x Magnification

Control 1, Pre-Weathering

Control 1, Post-Weathering

Control 2, Pre-Weathering

Control 2, Post-Weathering

Control 3, Pre-Weathering

Control 3, Post-Weathering

Surface Inspection with Leica MZ16a Microscope and photographs taken with a Nikon DS Fi-1 Camera with NIS Elements BR Software

Control:

10x Magnification

Control 4, Pre-Weathering

Control 4, Post-Weathering

Control 5, Pre-Weathering

Control 5, Post-Weathering

Control 6, Pre-Weathering

Control 6, Post-Weathering

Surface Inspection with Leica MZ16a Microscope and photographs taken with a Nikon DS Fi-1 Camera with NIS Elements BR Software

Allbäck Boiled Organic Linseed Oil:

1x Magnification

Linseed Oil 1, Pre-Weathering

Linseed Oil 1, Post-Weathering

Linseed Oil 2, Pre-Weathering

Linseed Oil 2, Post-Weathering

Linseed Oil 3, Pre-Weathering

Linseed Oil 3, Post-Weathering

Surface Inspection with Leica MZ16a Microscope and photographs taken with a Nikon DS Fi-1 Camera with NIS Elements BR Software

Allbäck Boiled Organic Linseed Oil:

1x Magnification

Linseed Oil 4, Pre-Weathering

Linseed Oil 4, Post-Weathering

Linseed Oil 5, Pre-Weathering

Linseed Oil 5, Post-Weathering

Linseed Oil 6, Pre-Weathering

Linseed Oil 6, Post-Weathering

Surface Inspection with Leica MZ16a Microscope and photographs taken with a Nikon DS Fi-1 Camera with NIS Elements BR Software

Allbäck Boiled Organic Linseed Oil:

10x Magnification

Linseed Oil 1, Pre-Weathering

Linseed Oil 1, Post-Weathering

Linseed Oil 2, Pre-Weathering

Linseed Oil 2, Post-Weathering

Linseed Oil 3, Pre-Weathering

Linseed Oil 3, Post-Weathering

Surface Inspection with Leica MZ16a Microscope and photographs taken with a Nikon DS Fi-1 Camera with NIS Elements BR Software

Allbäck Boiled Organic Linseed Oil:

10x Magnification

Linseed Oil 4, Pre-Weathering

Linseed Oil 4, Post-Weathering

Linseed Oil 5, Pre-Weathering

Linseed Oil 5, Post-Weathering

Linseed Oil 6, Pre-Weathering

Linseed Oil 6, Post-Weathering

Surface Inspection with Leica MZ16a Microscope and photographs taken with a Nikon DS Fi-1 Camera with NIS Elements BR Software

Paraffin and Mineral Spirits:

1x Magnification

Paraffin and Mineral Spirits 1, Pre-Weathering

Paraffin and Mineral Spirits 1, Post-Weathering

Paraffin and Mineral Spirits 2, Pre-Weathering

Paraffin and Mineral Spirits 2, Post-Weathering

Paraffin and Mineral Spirits 3, Pre-Weathering

Paraffin and Mineral Spirits 3, Post-Weathering

Surface Inspection with Leica MZ16a Microscope and photographs taken with a Nikon DS Fi-1 Camera with NIS Elements BR Software

Paraffin and Mineral Spirits:

1x Magnification

Paraffin and Mineral Spirits 4, Pre-Weathering

Paraffin and Mineral Spirits 4, Post-Weathering

Paraffin and Mineral Spirits 5, Pre-Weathering

Paraffin and Mineral Spirits 5, Post-Weathering

Paraffin and Mineral Spirits 6, Pre-Weathering

Paraffin and Mineral Spirits 6, Post-Weathering

Surface Inspection with Leica MZ16a Microscope and photographs taken with a Nikon DS Fi-1 Camera with NIS Elements BR Software

Paraffin and Mineral Spirits:

10x Magnification

Paraffin and Mineral Spirits 1, Pre-Weathering

Paraffin and Mineral Spirits 1, Post-Weathering

Paraffin and Mineral Spirits 2, Pre-Weathering

Paraffin and Mineral Spirits 2, Post-Weathering

Paraffin and Mineral Spirits 3, Pre-Weathering

Paraffin and Mineral Spirits 3, Post-Weathering

Surface Inspection with Leica MZ16a Microscope and photographs taken with a Nikon DS Fi-1 Camera with NIS Elements BR Software

Paraffin and Mineral Spirits:

10x Magnification

Paraffin and Mineral Spirits 4, Pre-Weathering

Paraffin and Mineral Spirits 4, Post-Weathering

Paraffin and Mineral Spirits 5, Pre-Weathering

Paraffin and Mineral Spirits 5, Post-Weathering

Paraffin and Mineral Spirits 6, Pre-Weathering

Paraffin and Mineral Spirits 6, Post-Weathering

Surface Inspection with Leica MZ16a Microscope and photographs taken with a Nikon DS Fi-1 Camera with NIS Elements BR Software

DEFY Extreme Exterior Clear Wood Stain:

1x Magnification

DEFY Extreme 1, Pre-Weathering

DEFY Extreme 1, Post-Weathering

DEFY Extreme 2, Pre-Weathering

DEFY Extreme 2, Post-Weathering

DEFY Extreme 3, Pre-Weathering

DEFY Extreme 3, Post-Weathering

Surface Inspection with Leica MZ16a Microscope and photographs taken with a Nikon DS Fi-1 Camera with NIS Elements BR Software

DEFY Extreme Exterior Clear Wood Stain:

1x Magnification

DEFY Extreme 4, Pre-Weathering

DEFY Extreme 4, Post-Weathering

DEFY Extreme 5, Pre-Weathering

DEFY Extreme 5, Post-Weathering

DEFY Extreme 6, Pre-Weathering

DEFY Extreme 6, Post-Weathering

Surface Inspection with Leica MZ16a Microscope and photographs taken with a Nikon DS Fi-1 Camera with NIS Elements BR Software

DEFY Extreme Exterior Clear Wood Stain:

10x Magnification

DEFY Extreme 1, Pre-Weathering

DEFY Extreme 1, Post-Weathering

DEFY Extreme 2, Pre-Weathering

DEFY Extreme 2, Post-Weathering

DEFY Extreme 3, Pre-Weathering

DEFY Extreme 3, Post-Weathering

Surface Inspection with Leica MZ16a Microscope and photographs taken with a Nikon DS Fi-1 Camera with NIS Elements BR Software

DEFY Extreme Exterior Clear Wood Stain:

10x Magnification

DEFY Extreme 4, Pre-Weathering

DEFY Extreme 4, Post-Weathering

DEFY Extreme 5, Pre-Weathering

DEFY Extreme 5, Post-Weathering

DEFY Extreme 6, Pre-Weathering

DEFY Extreme 6, Post-Weathering

Surface Inspection with Leica MZ16a Microscope and photographs taken with a Nikon DS Fi-1 Camera with NIS Elements BR Software

Armstrong's Wood Stain for Decks (Natural Tone):

1x Magnification

Armstrong's Wood Stain 1, Pre-Weathering

Armstrong's Wood Stain 1, Post-Weathering

Armstrong's Wood Stain 2, Pre-Weathering

Armstrong's Wood Stain 2, Post-Weathering

Armstrong's Wood Stain 3, Pre-Weathering

Armstrong's Wood Stain 3, Post-Weathering

Surface Inspection with Leica MZ16a Microscope and photographs taken with a Nikon DS Fi-1 Camera with NIS Elements BR Software

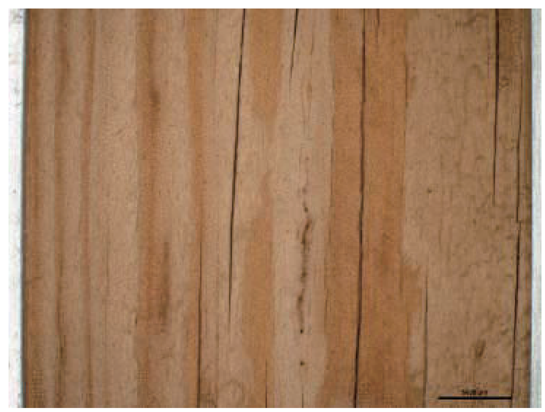
Armstrong's Wood Stain for Decks (Natural Tone):

1x Magnification

Armstrong's Wood Stain 4, Pre-Weathering

Armstrong's Wood Stain 4, Post-Weathering

Armstrong's Wood Stain 5, Pre-Weathering



Armstrong's Wood Stain 5, Post-Weathering

Armstrong's Wood Stain 6, Pre-Weathering

Armstrong's Wood Stain 6, Post-Weathering

Surface Inspection with Leica MZ16a Microscope and photographs taken with a Nikon DS Fi-1 Camera with NIS Elements BR Software

Armstrong's Wood Stain for Decks (Natural Tone):

10x Magnification

Armstrong's Wood Stain 1, Pre-Weathering

Armstrong's Wood Stain 1, Post-Weathering

Armstrong's Wood Stain 2, Pre-Weathering

Armstrong's Wood Stain 2, Post-Weathering

Armstrong's Wood Stain 3, Pre-Weathering

Armstrong's Wood Stain 3, Post-Weathering

Surface Inspection with Leica MZ16a Microscope and photographs taken with a Nikon DS Fi-1 Camera with NIS Elements BR Software

Armstrong's Wood Stain for Decks (Natural Tone):

10x Magnification

Armstrong's Wood Stain 4, Pre-Weathering

Armstrong's Wood Stain 4, Post-Weathering

Armstrong's Wood Stain 5, Pre-Weathering

Armstrong's Wood Stain 5, Post-Weathering

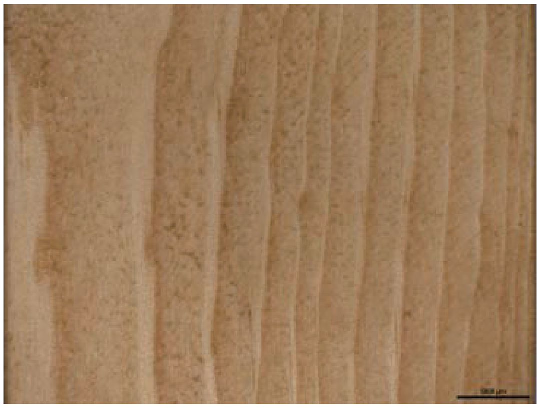
Armstrong's Wood Stain 6, Pre-Weathering

Armstrong's Wood Stain 6, Post-Weathering

Surface Inspection with Leica MZ16a Microscope and photographs taken with a Nikon DS Fi-1 Camera with NIS Elements BR Software

TWP 1500 Natural Stain (Natural Tone):

1x Magnification



TWP 1500 1, Pre-Weathering

TWP 1500 1, Post-Weathering

TWP 1500 2, Pre-Weathering

TWP 1500 2, Post-Weathering

TWP 1500 3, Pre-Weathering

TWP 1500 3, Post-Weathering

Surface Inspection with Leica MZ16a Microscope and photographs taken with a Nikon DS Fi-1 Camera with NIS Elements BR Software

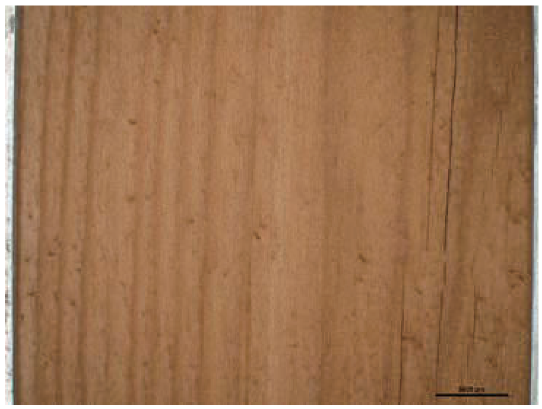
TWP 1500 Natural Stain (Natural Tone):

1x Magnification

TWP 1500 4, Pre-Weathering

TWP 1500 4, Post-Weathering

TWP 1500 5, Pre-Weathering



TWP 1500 5, Post-Weathering

TWP 1500 6, Pre-Weathering

TWP 1500 6, Post-Weathering

Surface Inspection with Leica MZ16a Microscope and photographs taken with a Nikon DS Fi-1 Camera with NIS Elements BR Software

TWP 1500 Natural Stain (Natural Tone):

10x Magnification

TWP 1500 1, Pre-Weathering

TWP 1500 1, Post-Weathering

TWP 1500 2, Pre-Weathering

TWP 1500 2, Post-Weathering

TWP 1500 3, Pre-Weathering

TWP 1500 3, Post-Weathering

Surface Inspection with Leica MZ16a Microscope and photographs taken with a Nikon DS Fi-1 Camera with NIS Elements BR Software

TWP 1500 Natural Stain (Natural Tone):

10x Magnification

TWP 1500 4, Pre-Weathering

TWP 1500 4, Post-Weathering

TWP 1500 5, Pre-Weathering

TWP 1500 5, Post-Weathering

TWP 1500 6, Pre-Weathering

TWP 1500 6, Post-Weathering

Surface Inspection with Leica MZ16a Microscope and photographs taken with a Nikon DS Fi-1 Camera with NIS Elements BR Software

Flood CWF UV-5 Penetrating Wood Finish for Fences, Decks, and Siding (Natural Tone (Clear)):

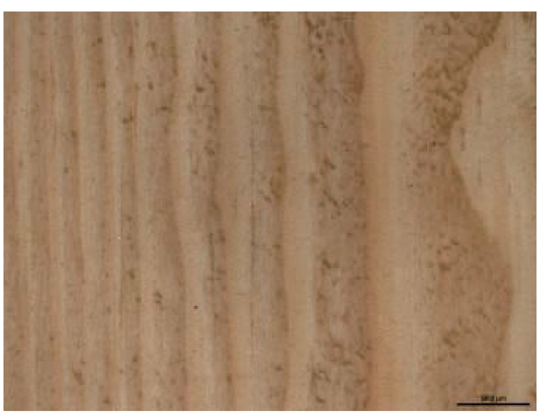
1x Magnification

Flood CWF UV-5 1, Pre-Weathering

Flood CWF UV-5 1, Post-Weathering

Flood CWF UV-5 2, Pre-Weathering

Flood CWF UV-5 2, Post-Weathering



Flood CWF UV-5 3, Pre-Weathering

Flood CWF UV-5 3, Post-Weathering

Surface Inspection with Leica MZ16a Microscope and photographs taken with a Nikon DS Fi-1 Camera with NIS Elements BR Software

Flood CWF UV-5 Penetrating Wood Finish for Fences, Decks, and Siding (Natural Tone (Clear)):

1x Magnification

Flood CWF UV-5 4, Pre-Weathering

Flood CWF UV-5 4, Post-Weathering

Flood CWF UV-5 5, Pre-Weathering

Flood CWF UV-5 5, Post-Weathering

Flood CWF UV-5 6, Pre-Weathering

Flood CWF UV-5 6, Post-Weathering

Surface Inspection with Leica MZ16a Microscope and photographs taken with a Nikon DS Fi-1 Camera with NIS Elements BR Software

Flood CWF UV-5 Penetrating Wood Finish for Fences, Decks, and Siding (Natural Tone (Clear)): 10x Magnification

Flood CWF UV-5 1, Pre-Weathering

Flood CWF UV-5 1, Post-Weathering

Flood CWF UV-5 2, Pre-Weathering

Flood CWF UV-5 2, Post-Weathering

Flood CWF UV-5 3, Pre-Weathering

Flood CWF UV-5 3, Post-Weathering

Surface Inspection with Leica MZ16a Microscope and photographs taken with a Nikon DS Fi-1 Camera with NIS Elements BR Software

Flood CWF UV-5 Penetrating Wood Finish for Fences, Decks, and Siding (Natural Tone (Clear)): 10x Magnification

Flood CWF UV-5 4, Pre-Weathering

Flood CWF UV-5 4, Post-Weathering

Flood CWF UV-5 5, Pre-Weathering

Flood CWF UV-5 5, Post-Weathering

Flood CWF UV-5 6, Pre-Weathering

Flood CWF UV-5 6, Post-Weathering

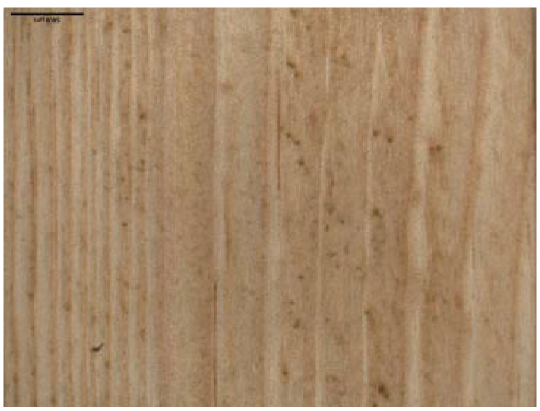
Surface Inspection with Leica MZ16a Microscope and photographs taken with a Nikon DS Fi-1 Camera with NIS Elements BR Software

Messmer's U.V. Plus Exterior Wood Finish (Natural):

1x Magnification

Messmer's UV Plus 1, Pre-Weathering

Messmer's UV Plus 1, Post-Weathering



Messmer's UV Plus 2, Pre-Weathering

Messmer's UV Plus 2, Post-Weathering

Messmer's UV Plus 3, Pre-Weathering

Messmer's UV Plus 3, Post-Weathering

Surface Inspection with Leica MZ16a Microscope and photographs taken with a Nikon DS Fi-1 Camera with NIS Elements BR Software

Messmer's U.V. Plus Exterior Wood Finish (Natural):

1x Magnification

Messmer's UV Plus 4, Pre-Weathering

Messmer's UV Plus 4, Post-Weathering

Messmer's UV Plus 5, Pre-Weathering

Messmer's UV Plus 5, Post-Weathering

Messmer's UV Plus 6, Pre-Weathering

Messmer's UV Plus 6, Post-Weathering

Surface Inspection with Leica MZ16a Microscope and photographs taken with a Nikon DS Fi-1 Camera with NIS Elements BR Software

Messmer's U.V. Plus Exterior Wood Finish (Natural):

10x Magnification

Messmer's UV Plus 1, Pre-Weathering

Messmer's UV Plus 1, Post-Weathering

Messmer's UV Plus 2, Pre-Weathering

Messmer's UV Plus 2, Post-Weathering

Messmer's UV Plus 3, Pre-Weathering

Messmer's UV Plus 3, Post-Weathering

Surface Inspection with Leica MZ16a Microscope and photographs taken with a Nikon DS Fi-1 Camera with NIS Elements BR Software

Messmer's U.V. Plus Exterior Wood Finish (Natural):

10x Magnification

Messmer's UV Plus 4, Pre-Weathering

Messmer's UV Plus 4, Post-Weathering

Messmer's UV Plus 5, Pre-Weathering

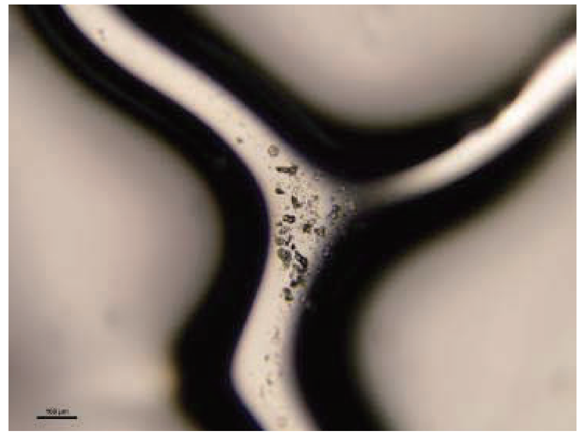
Messmer's UV Plus 5, Post-Weathering

Messmer's UV Plus 6, Pre-Weathering

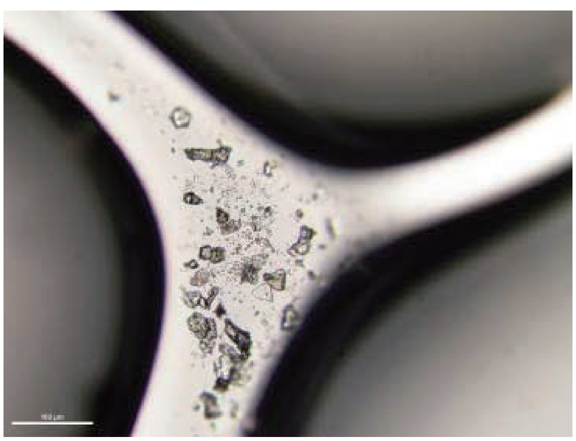
Messmer's UV Plus 6, Post-Weathering

Stain Inspection with Olympus CX31 Microscope and photographs taken with a Nikon DS Fi-1 Camera with NIS Elements BR Software
Allbäck Boiled Organic Linseed Oil:

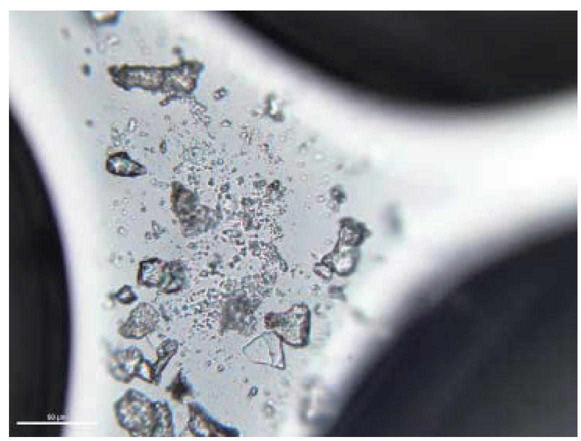
Ocular Mag: 10x, Trinocular Mag: 0.6x, Objective Mag: 4x



Ocular Mag: 10x, Trinocular Mag: 0.6x, Objective Mag: 10x



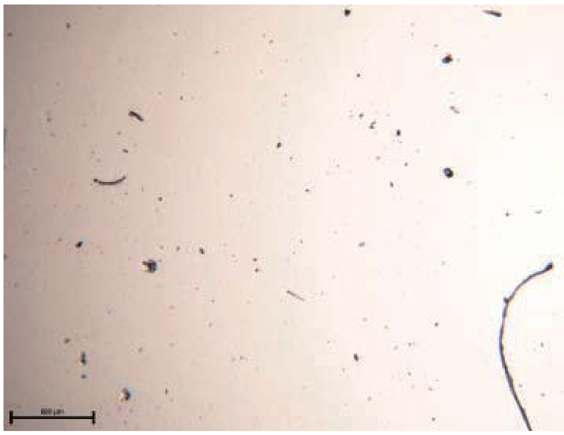
Ocular Mag: 10x, Trinocular Mag: 0.6x, Objective Mag: 20x



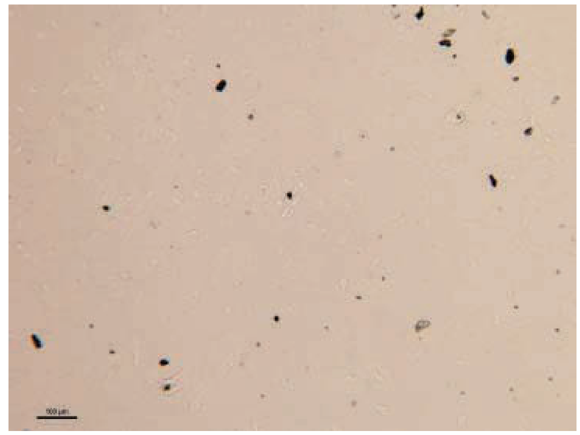
Ocular Mag: 10x, Trinocular Mag: 0.6x, Objective Mag: 40x

Stain Inspection with Olympus CX31 Microscope and photographs taken with a Nikon DS Fi-1 Camera with NIS Elements BR Software

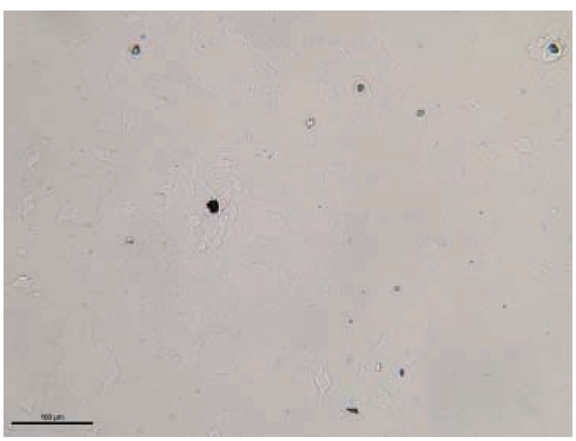
Paraffin and Mineral Spirits:



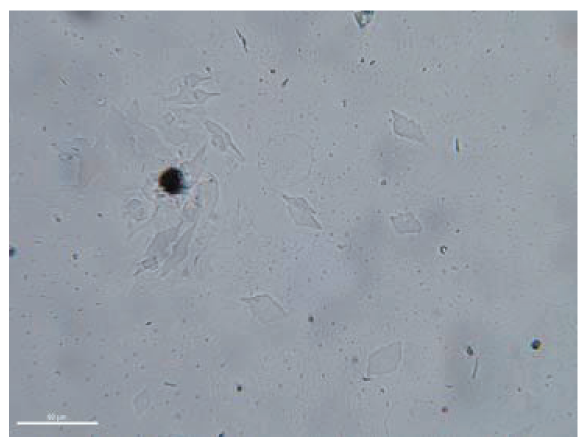
Ocular Mag: 10x, Trinocular Mag: 0.6x, Objective Mag: 4x



Ocular Mag: 10x, Trinocular Mag: 0.6x, Objective Mag: 10x

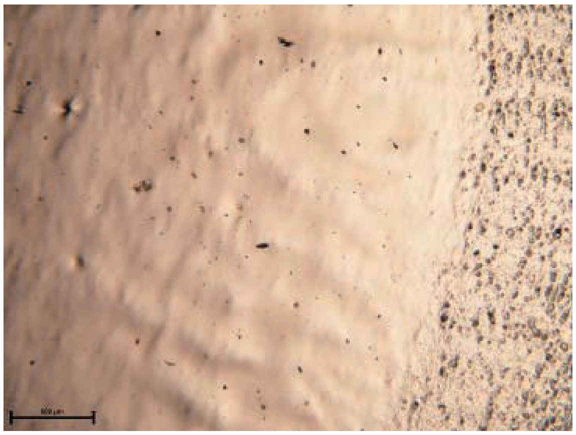


Ocular Mag: 10x, Trinocular Mag: 0.6x, Objective Mag: 20x

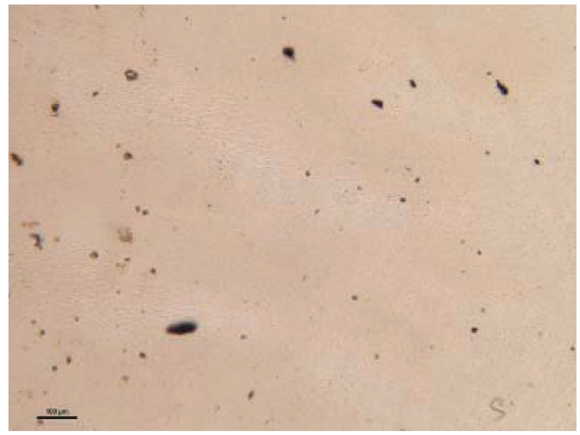


Ocular Mag: 10x, Trinocular Mag: 0.6x, Objective Mag: 40x

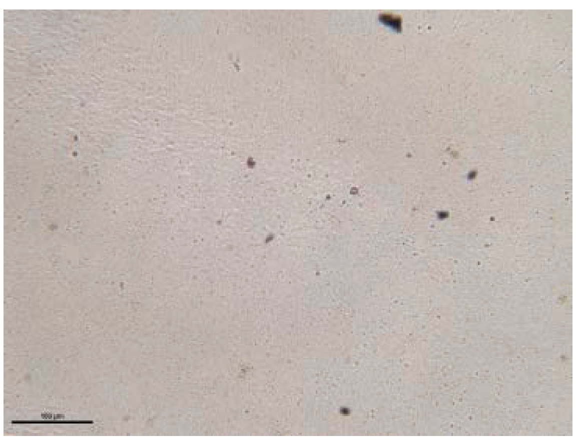
Stain Inspection with Olympus CX31 Microscope and photographs taken with a Nikon DS Fi-1 Camera with NIS Elements BR Software
DEFY Extreme Exterior Clear Wood Stain:



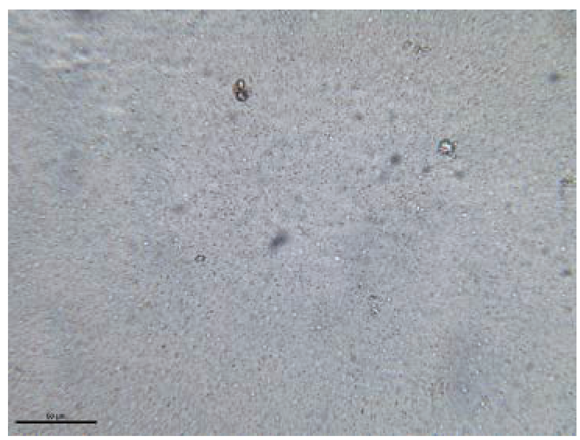
Ocular Mag: 10x, Trinocular Mag: 0.6x, Objective Mag: 4x



Ocular Mag: 10x, Trinocular Mag: 0.6x, Objective Mag: 10x

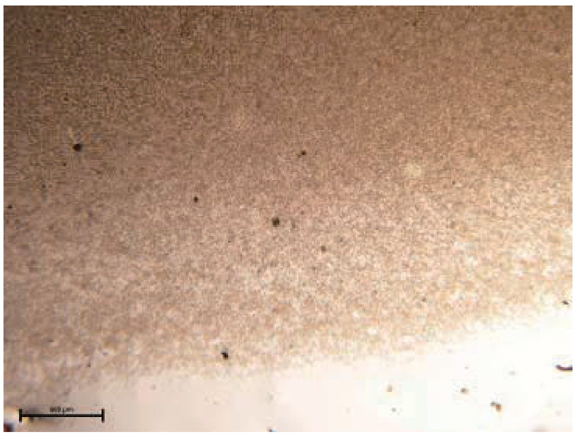


Ocular Mag: 10x, Trinocular Mag: 0.6x, Objective Mag: 20x

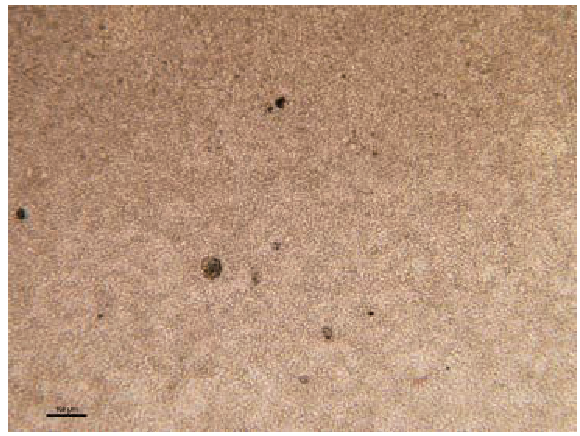


Ocular Mag: 10x, Trinocular Mag: 0.6x, Objective Mag: 40x

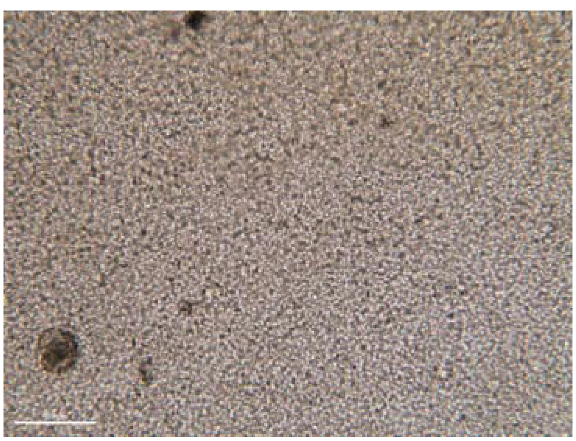
Stain Inspection with Olympus CX31 Microscope and photographs taken with a Nikon DS Fi-1 Camera with NIS Elements BR Software
Armstrong's Wood Stain for Decks (Natural Tone):



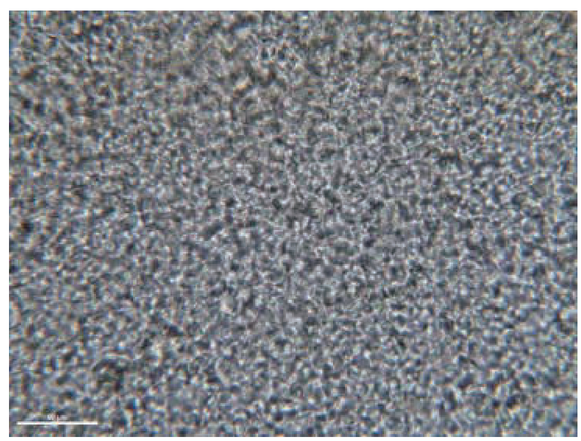
Ocular Mag: 10x, Trinocular Mag: 0.6x, Objective Mag: 4x



Ocular Mag: 10x, Trinocular Mag: 0.6x, Objective Mag: 10x

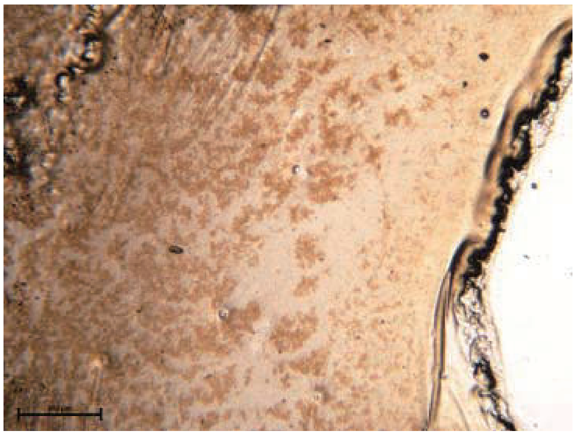


Ocular Mag: 10x, Trinocular Mag: 0.6x, Objective Mag: 20x

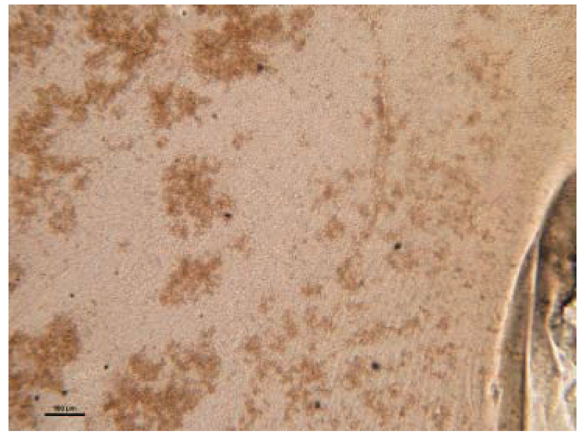


Ocular Mag: 10x, Trinocular Mag: 0.6x, Objective Mag: 40x

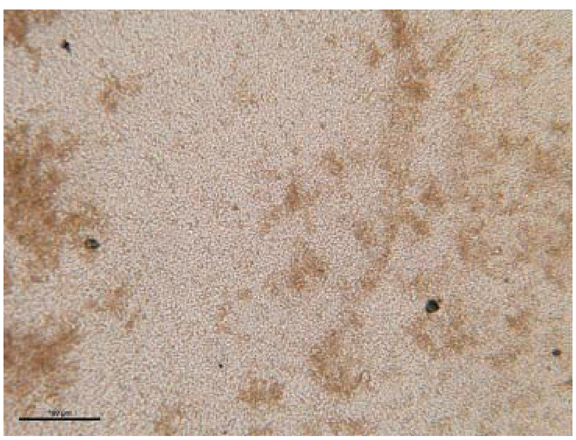
Stain Inspection with Olympus CX31 Microscope and photographs taken with a Nikon DS Fi-1 Camera with NIS Elements BR Software
TWP 1500 Natural Stain (Natural Tone):



Ocular Mag: 10x, Trinocular Mag: 0.6x, Objective Mag: 4x



Ocular Mag: 10x, Trinocular Mag: 0.6x, Objective Mag: 10x

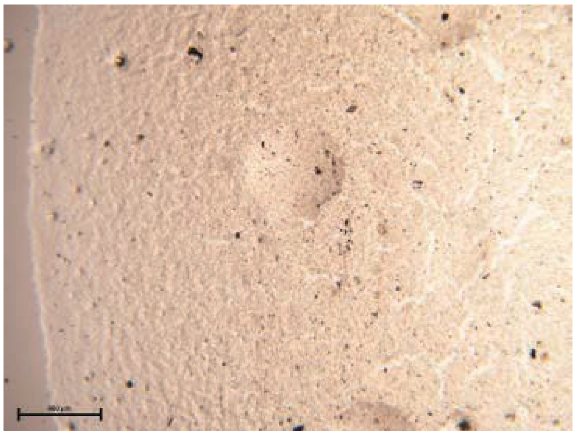


Ocular Mag: 10x, Trinocular Mag: 0.6x, Objective Mag: 20x

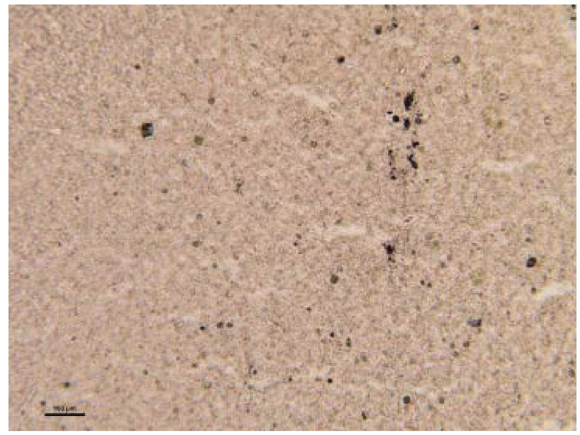
Ocular Mag: 10x, Trinocular Mag: 0.6x, Objective Mag: 40x

Stain Inspection with Olympus CX31 Microscope and photographs taken with a Nikon DS Fi-1 Camera with NIS Elements BR Software

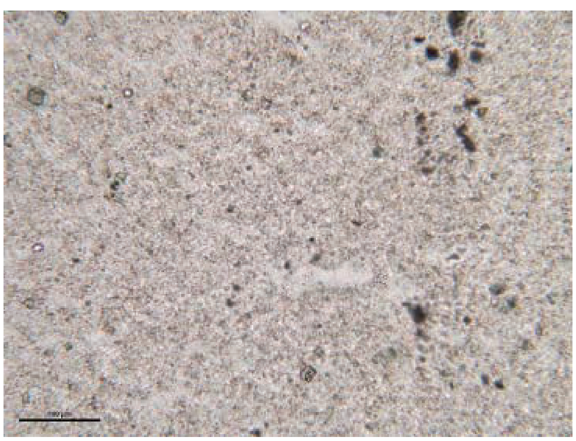
Flood CWF UV-5 Penetrating Wood Finish for Fences, Decks, and Siding (Natural Tone (Clear)):



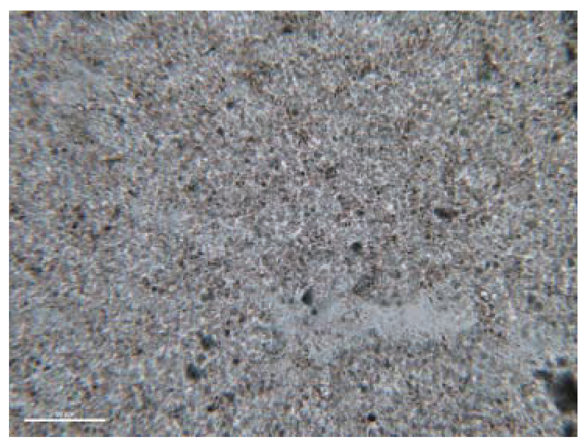
Ocular Mag: 10x, Trinocular Mag: 0.6x, Objective Mag: 4x



Ocular Mag: 10x, Trinocular Mag: 0.6x, Objective Mag: 10x

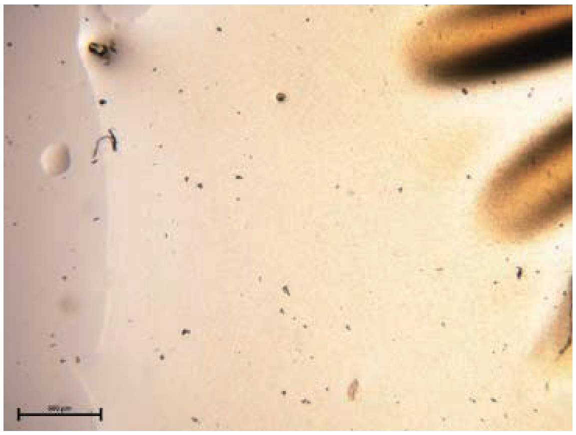


Ocular Mag: 10x, Trinocular Mag: 0.6x, Objective Mag: 20x

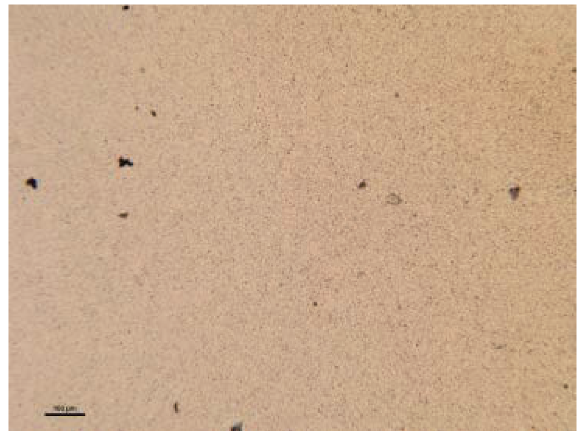


Ocular Mag: 10x, Trinocular Mag: 0.6x, Objective Mag: 40x

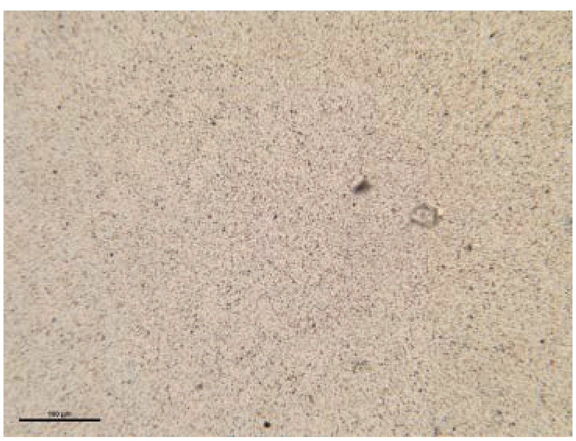
Stain Inspection with Olympus CX31 Microscope and photographs taken with a Nikon DS Fi-1 Camera with NIS Elements BR Software
Messmer's U.V. Plus Exterior Wood Finish (Natural):



Ocular Mag: 10x, Trinocular Mag: 0.6x,
Objective Mag: 4x



Ocular Mag: 10x, Trinocular Mag: 0.6x,
Objective Mag: 10x



Ocular Mag: 10x, Trinocular Mag: 0.6x,
Objective Mag: 20x

Ocular Mag: 10x, Trinocular Mag: 0.6x,
Objective Mag: 40x

Appendix C - Color Changes

Summary of Color Changes:

	Sample	Before and After Treatment (ΔE)	Before and After Weathering (ΔE)	Weathered Sample to Weathered Control (ΔE)
Control				
	CON-1	n/a	21.94	n/a
	CON-2	n/a	21.00	n/a
	CON-3	n/a	24.67	n/a
	CON-4	n/a	21.75	n/a
	CON-5	n/a	26.53	n/a
	CON-6	n/a	32.25	n/a
	Average	n/a	24.69	n/a
Linseed Oil				
	LIN-1	17.30	31.80	16.74
	LIN-2	19.10	32.92	19.76
	LIN-3	15.25	25.70	5.33
	LIN-4	13.80	28.98	8.03
	LIN-5	19.71	28.42	14.45
	LIN-6	18.19	27.67	19.63
	Average	17.23	29.25	13.99
Paraffin and Mineral Spirits				
	PAR-1	1.64	25.16	8.27
	PAR-2	3.10	23.21	3.41
	PAR-3	1.41	21.71	6.51
	PAR-4	5.94	19.93	2.55
	PAR-5	2.27	32.79	4.61
	PAR-6	1.19	31.69	8.78
	Average	2.59	25.75	5.69
DEFY Extreme (Clear)				
	DEF-1	1.52	34.97	9.89
	DEF-2	2.20	35.11	9.72
	DEF-3	4.23	28.44	7.33
	DEF-4	9.51	26.82	5.88
	DEF-5	5.41	23.61	6.78
	DEF-6	1.82	31.31	10.21
	Average	4.12	30.04	8.30

Summary of Color Changes:

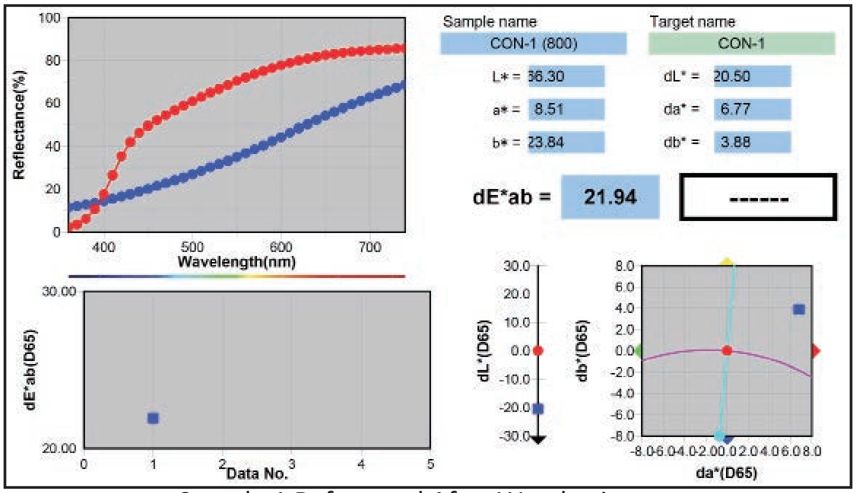
	Sample	Before and After Treatment (ΔE)	Before and After Weathering (ΔE)	Weathered Sample to Weathered Control (ΔE)
Armstrong (Natural)				
	ARM-1	21.13	22.16	9.59
	ARM-2	20.88	22.67	10.20
	ARM-3	21.16	18.23	6.82
	ARM-4	22.89	15.52	5.86
	ARM-5	22.47	23.01	10.94
	ARM-6	19.11	21.31	10.10
	Average	21.27	20.48	8.92
TWP 1500 (Natural)				
	TWP-1	26.91	16.59	9.67
	TWP-2	29.89	14.57	10.53
	TWP-3	27.46	12.50	13.69
	TWP-4	20.71	15.50	14.02
	TWP-5	27.15	15.64	17.87
	TWP-6	29.22	17.77	19.55
	Average	26.89	15.43	14.22
Flood CWF UV-5 (Natural)				
	FLO-1	22.06	23.55	20.02
	FLO-2	22.68	25.60	19.49
	FLO-3	21.99	29.93	25.86
	FLO-4	21.29	28.70	24.55
	FLO-5	27.15	25.30	22.66
	FLO-6	22.12	24.73	23.25
	Average	22.88	26.30	22.64
Messmer's UV Plus (Natural)				
	MES-1	30.27	17.37	18.93
	MES-2	31.02	21.96	19.44
	MES-3	29.03	19.72	20.46
	MES-4	31.55	22.61	20.63
	MES-5	26.06	22.55	21.26
	MES-6	29.37	16.07	23.78
	Average	29.55	20.05	20.75

Summary of Color Changes:

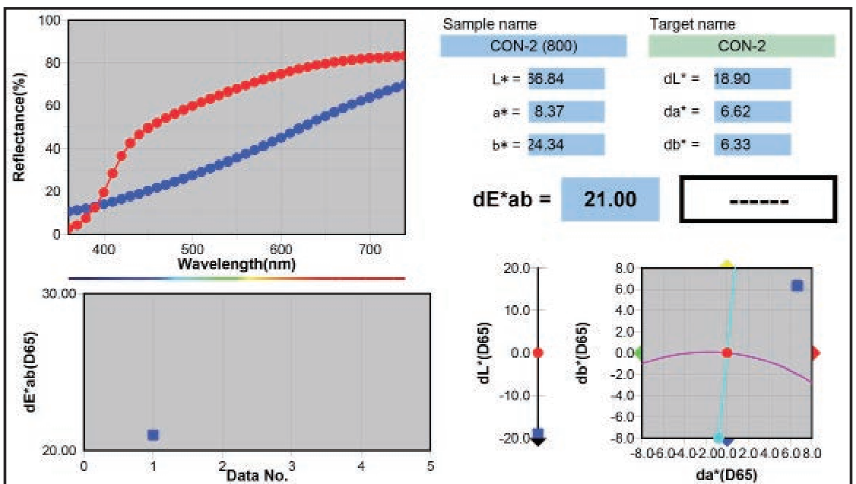
	Sample	Before and After Treatment (ΔE)	Before and After Weathering (ΔE)	Weathered Sample to Weathered Control (ΔE)
Curved				
	CON-CURV	n/a	n/a	n/a
	LIN-CURV	n/a	n/a	13.44
	PAR-CURV	n/a	n/a	7.34
	DEF-CURV	n/a	n/a	7.70
	ARM-CURV	n/a	n/a	5.08
	TWP-CURV	n/a	n/a	7.69
	FLO-CURV	n/a	n/a	13.98
	MES-CURV	n/a	n/a	15.65

Color Changes:

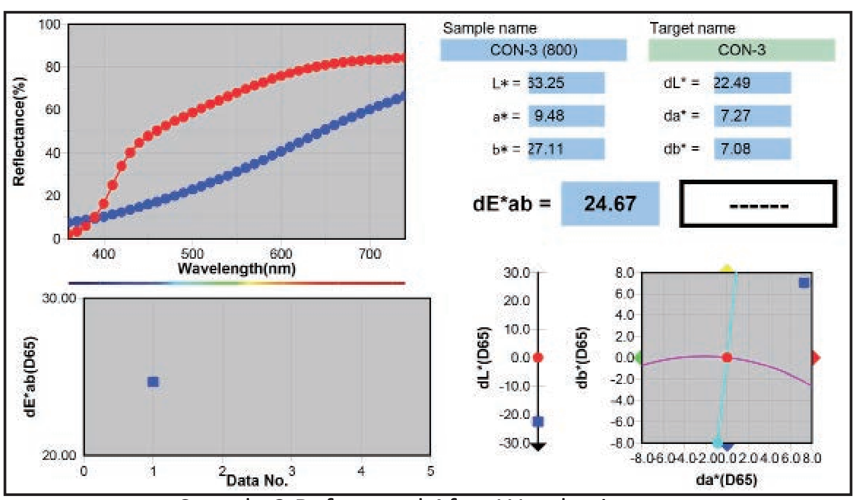
Control:



Sample 1 Before and After Weathering



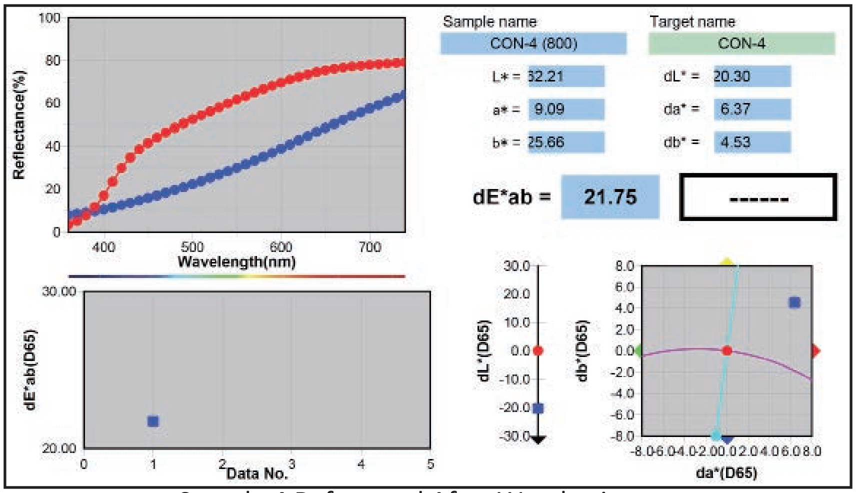
Sample 2 Before and After Weathering



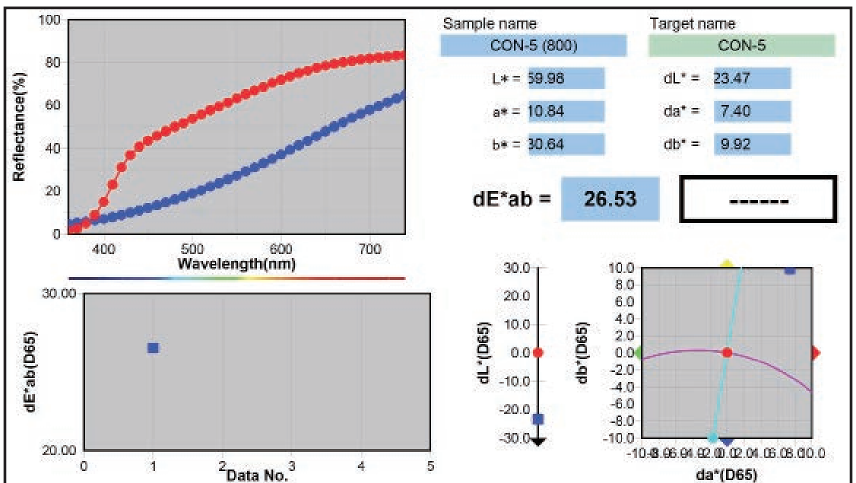
Sample 3 Before and After Weathering

Color Changes:

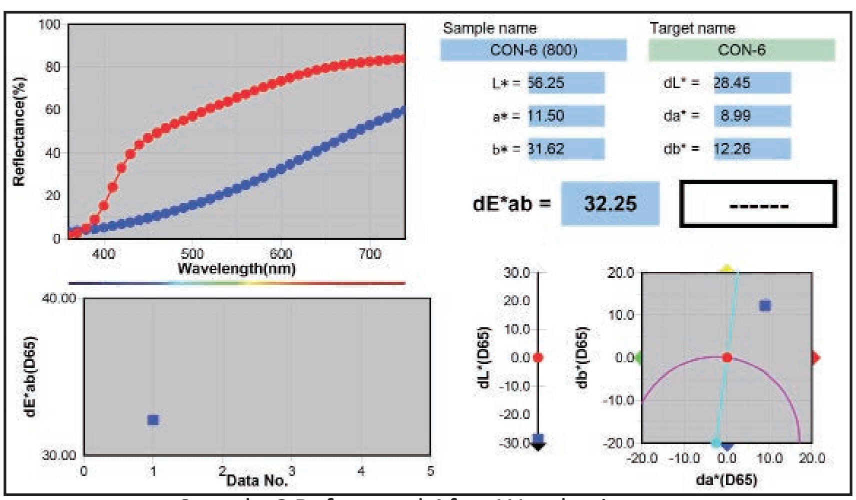
Control:



Sample 4 Before and After Weathering



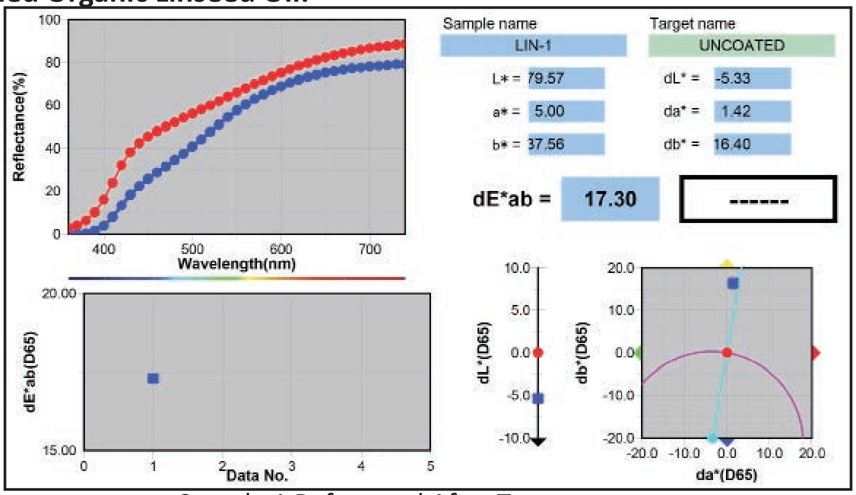
Sample 5 Before and After Weathering



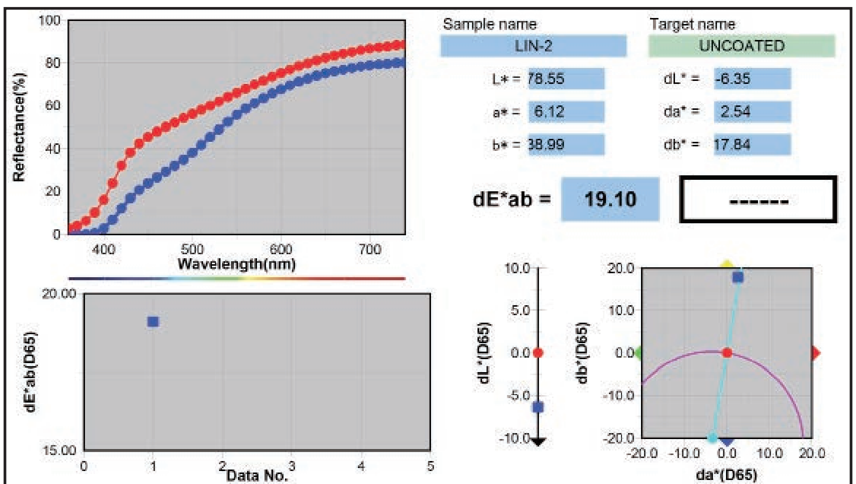
Sample 6 Before and After Weathering

Color Changes:

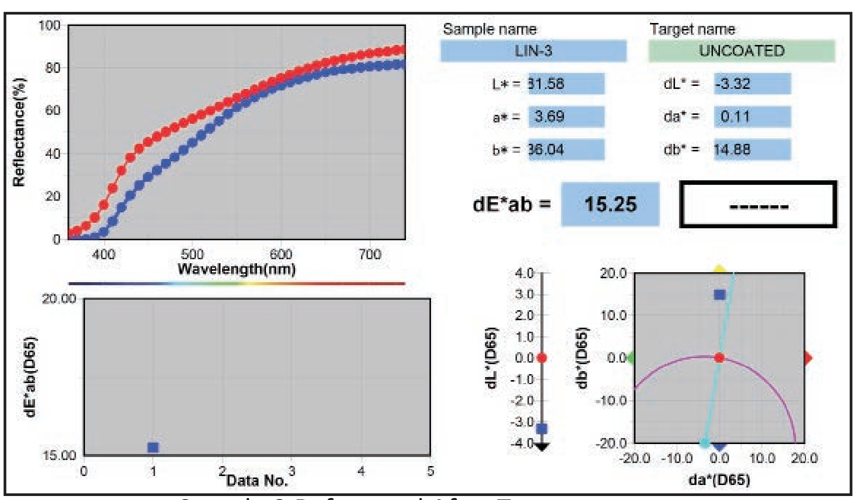
Allbäck Boiled Organic Linseed Oil:



Sample 1 Before and After Treatment



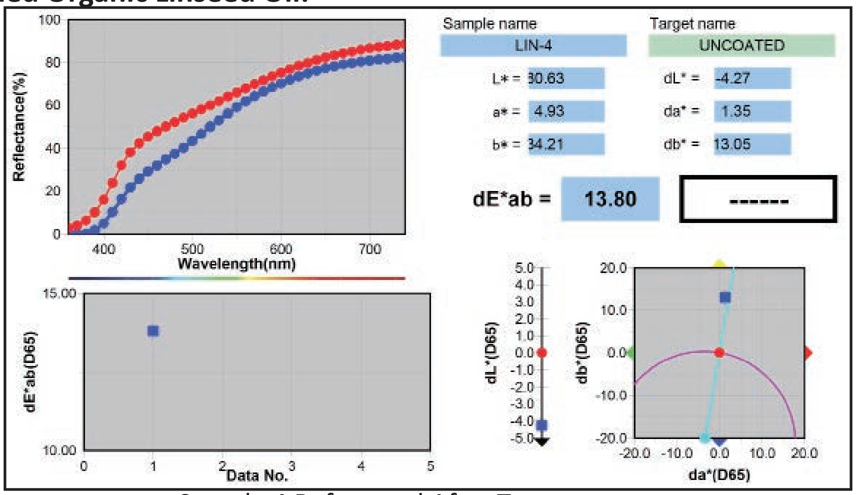
Sample 2 Before and After Treatment



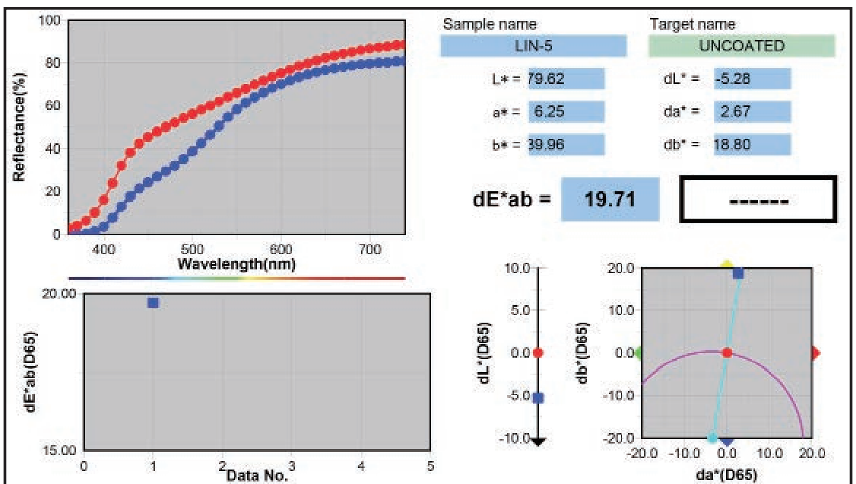
Sample 3 Before and After Treatment

Color Changes:

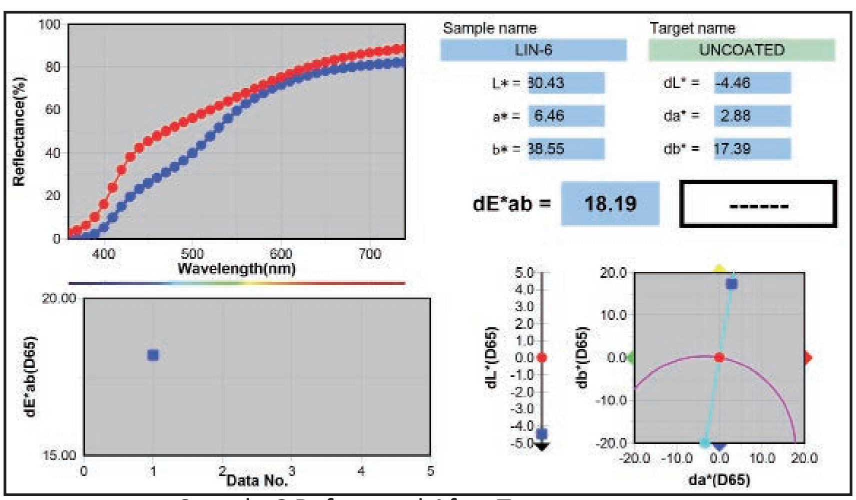
Allbäck Boiled Organic Linseed Oil:



Sample 4 Before and After Treatment



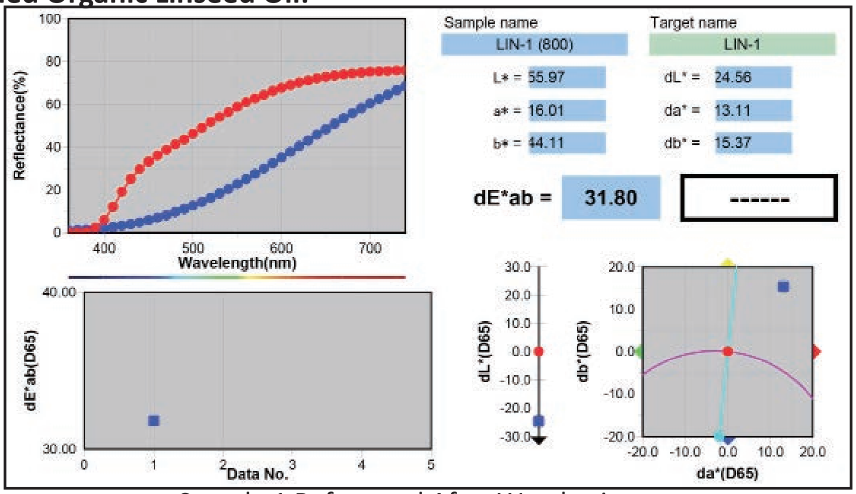
Sample 5 Before and After Treatment



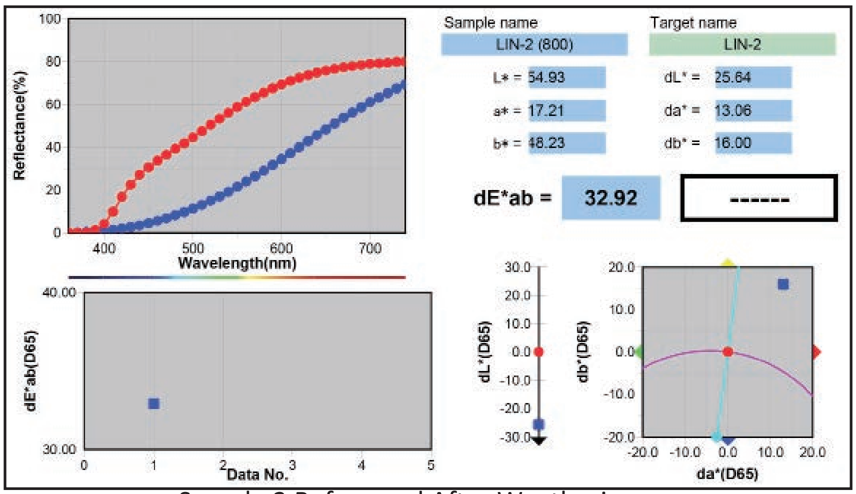
Sample 6 Before and After Treatment

Color Changes:

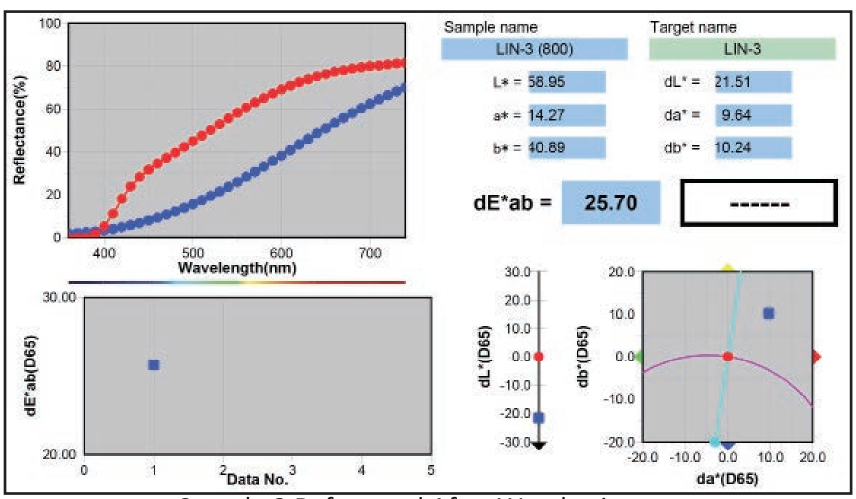
Allbäck Boiled Organic Linseed Oil:



Sample 1 Before and After Weathering



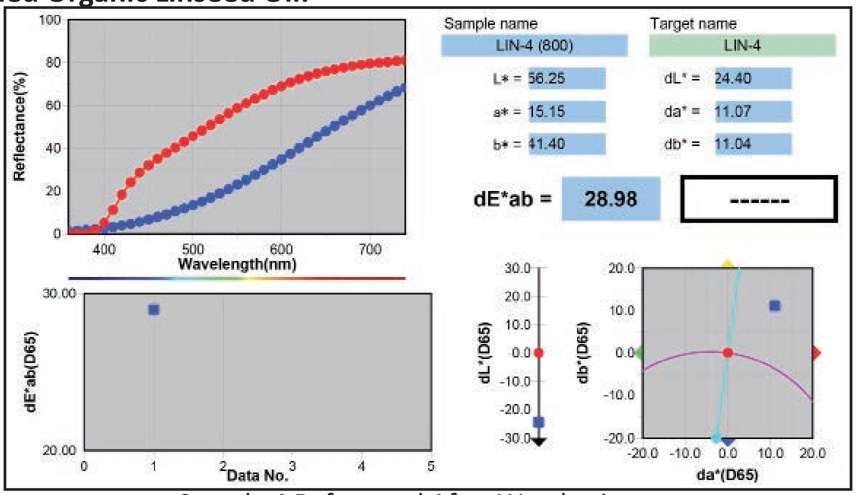
Sample 2 Before and After Weathering



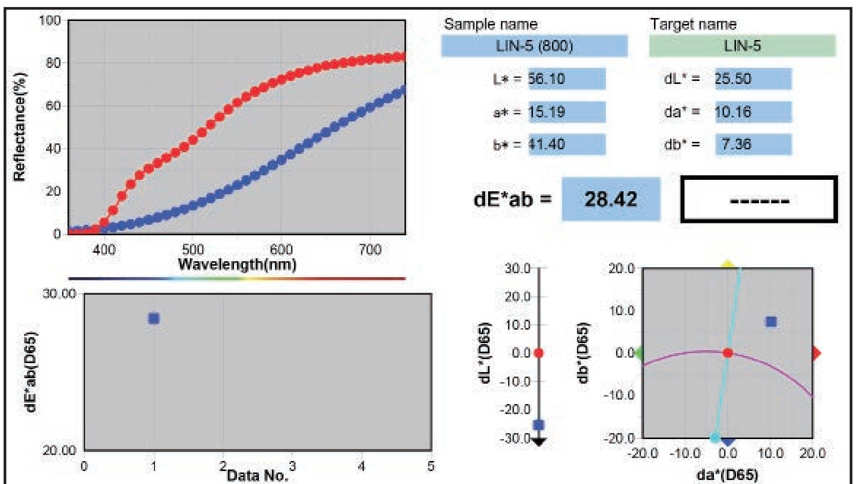
Sample 3 Before and After Weathering

Color Changes:

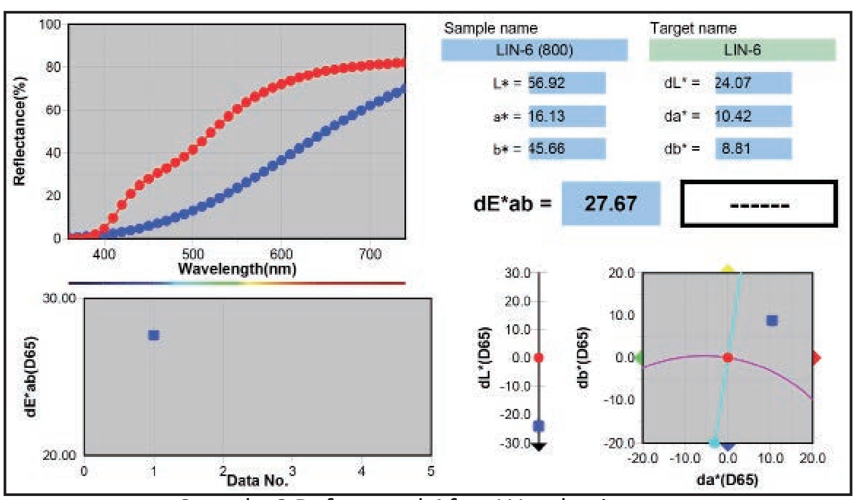
Allbäck Boiled Organic Linseed Oil:



Sample 4 Before and After Weathering



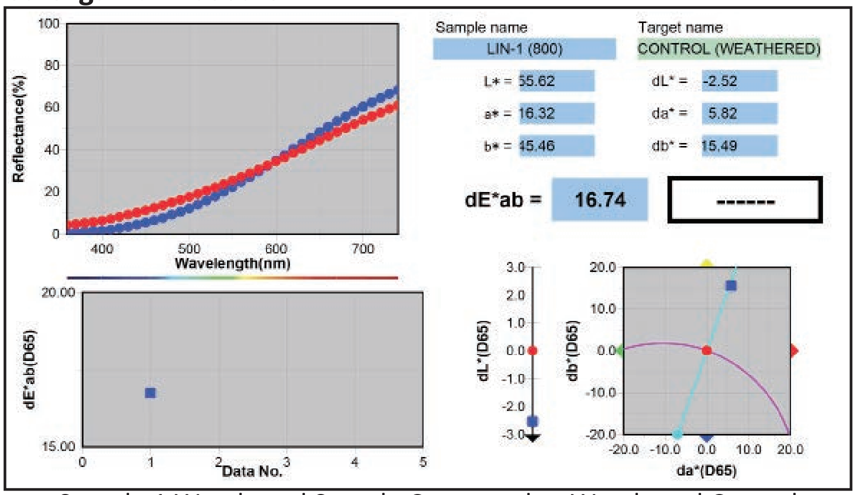
Sample 5 Before and After Weathering



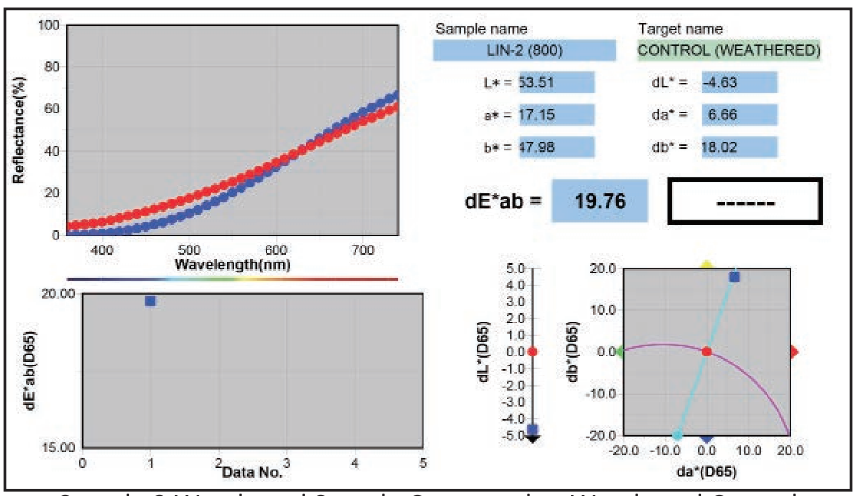
Sample 6 Before and After Weathering

Color Changes:

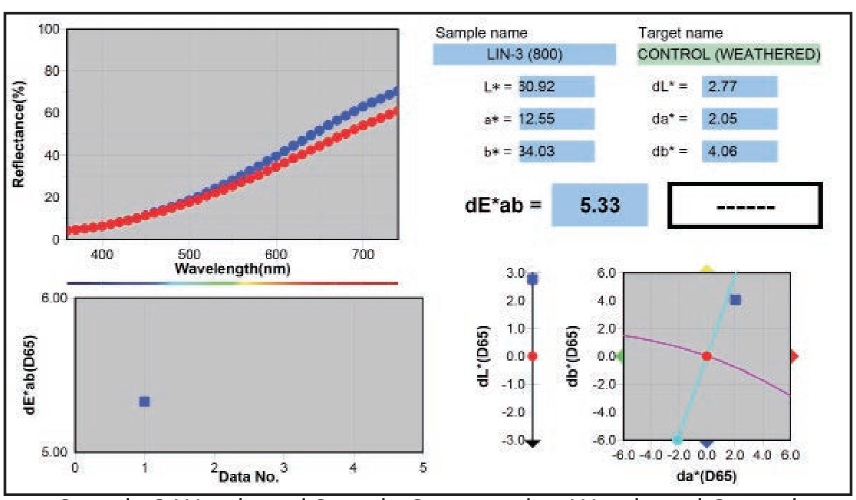
Allbäck Boiled Organic Linseed Oil:



Sample 1 Weathered Sample Compared to Weathered Control



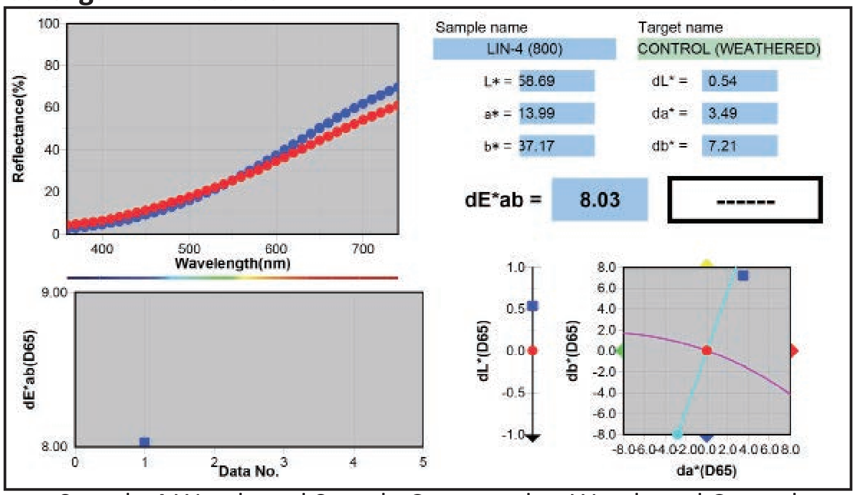
Sample 2 Weathered Sample Compared to Weathered Control



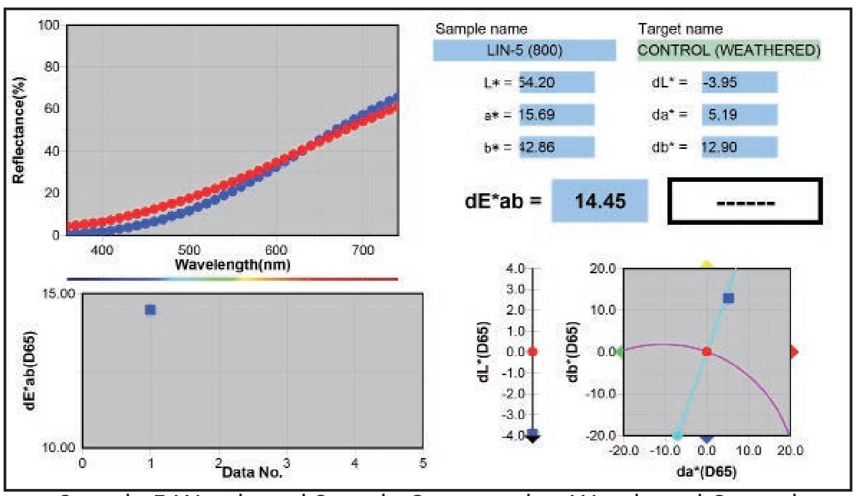
Sample 3 Weathered Sample Compared to Weathered Control

Color Changes:

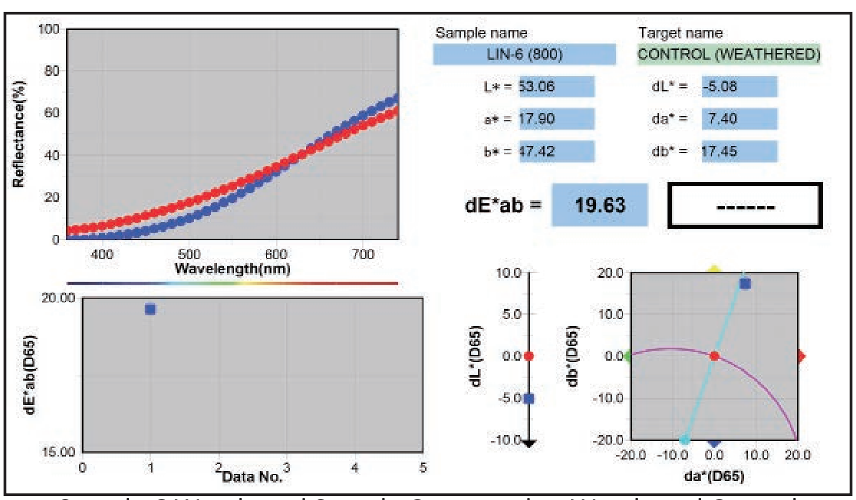
Allbäck Boiled Organic Linseed Oil:



Sample 4 Weathered Sample Compared to Weathered Control



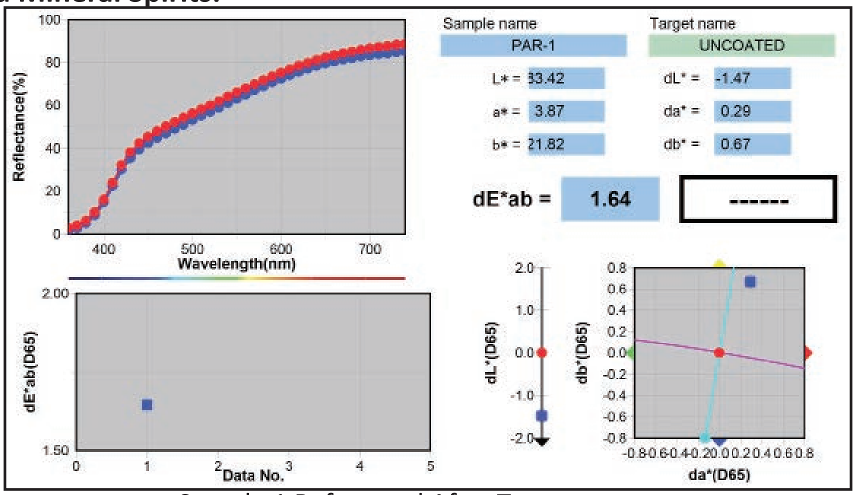
Sample 5 Weathered Sample Compared to Weathered Control



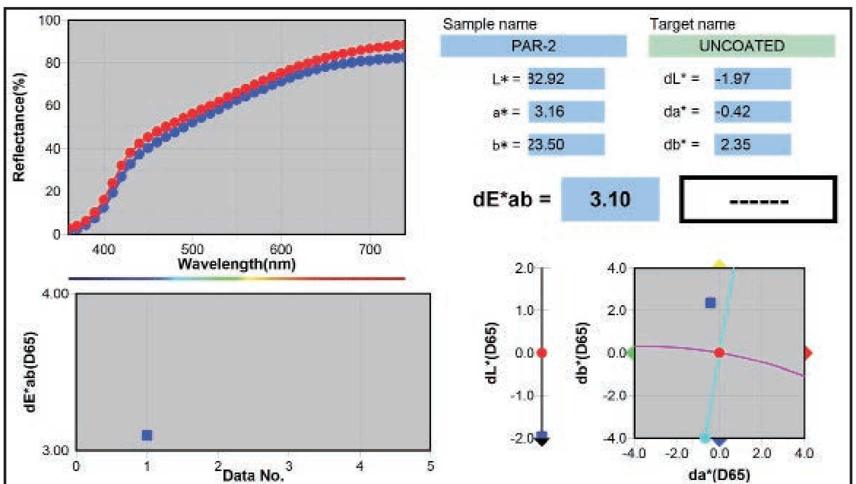
Sample 6 Weathered Sample Compared to Weathered Control

Color Changes:

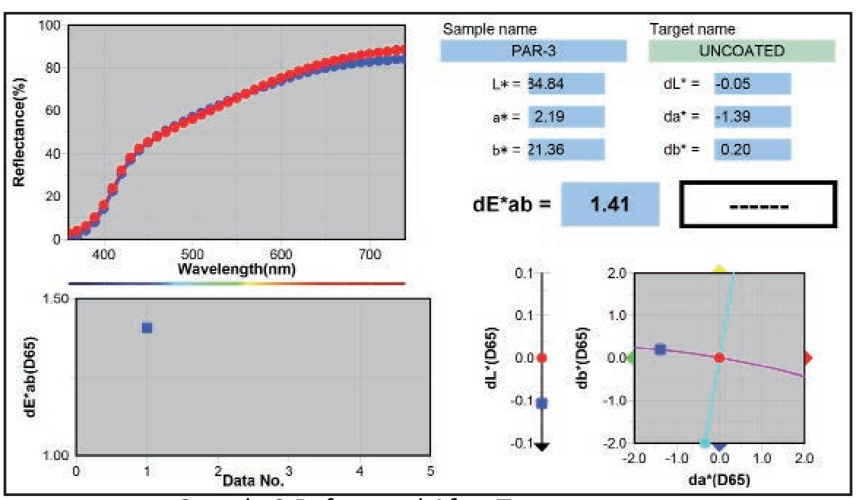
Paraffin and Mineral Spirits:



Sample 1 Before and After Treatment



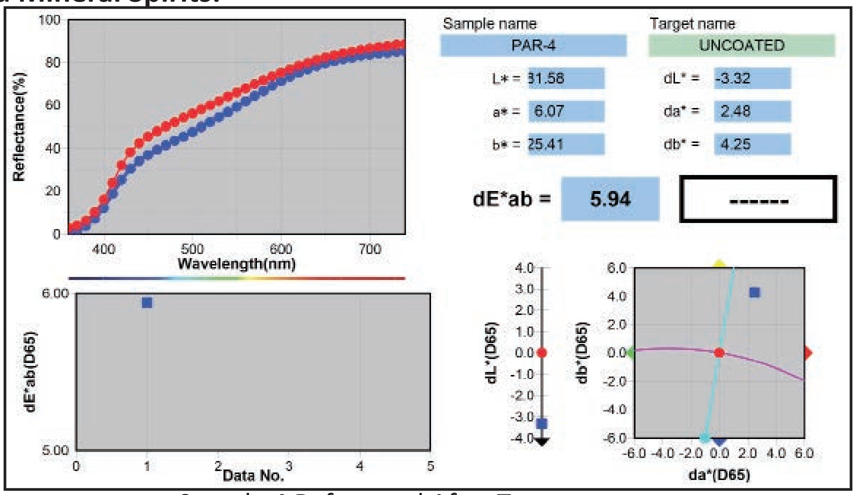
Sample 2 Before and After Treatment



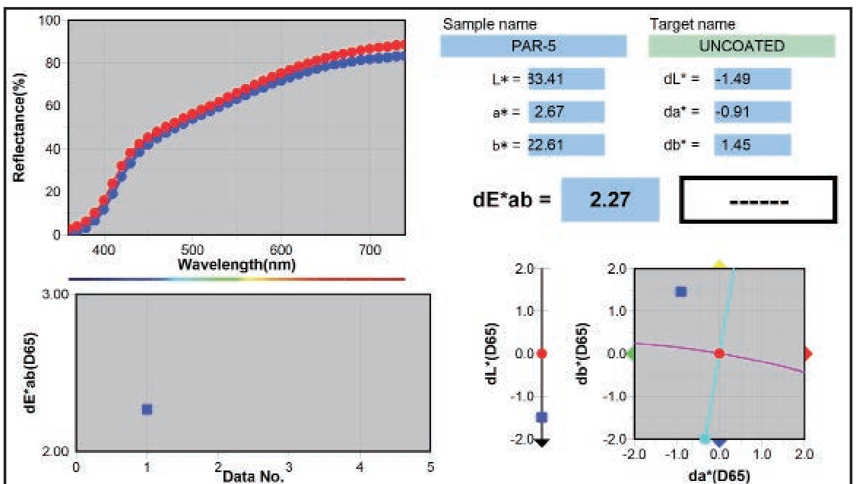
Sample 3 Before and After Treatment

Color Changes:

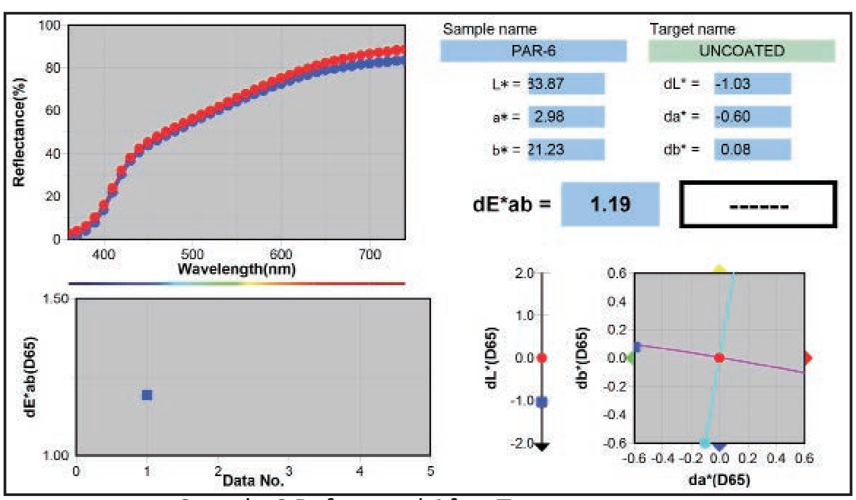
Paraffin and Mineral Spirits:



Sample 4 Before and After Treatment

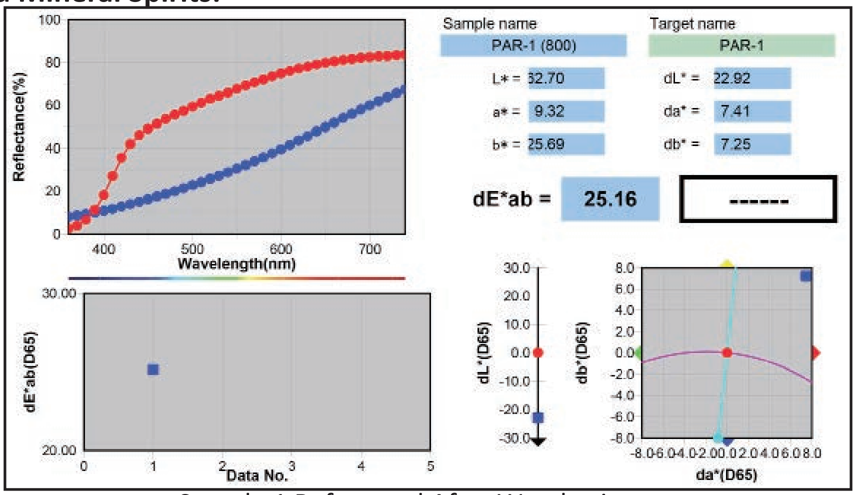


Sample 5 Before and After Treatment

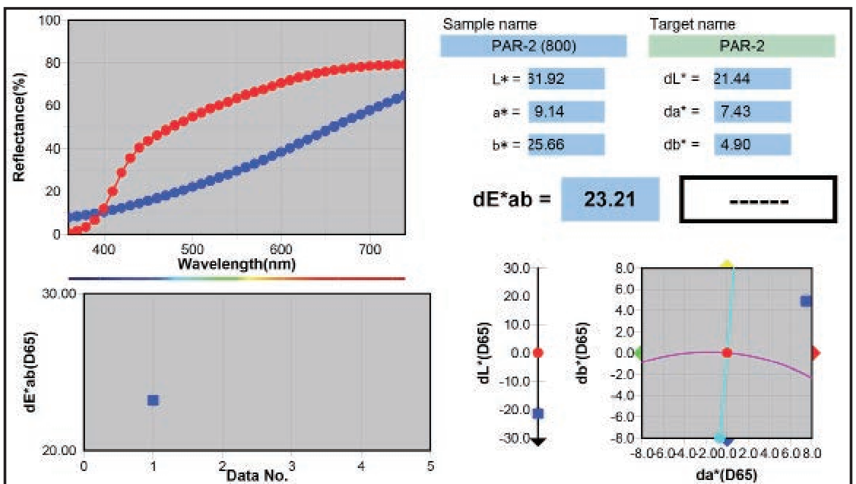


Sample 6 Before and After Treatment

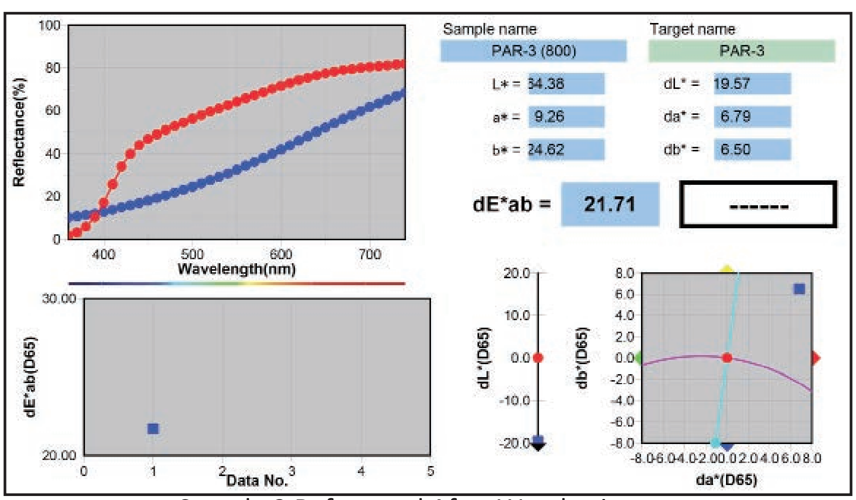
Color Changes:
Paraffin and Mineral Spirits:



Sample 1 Before and After Weathering



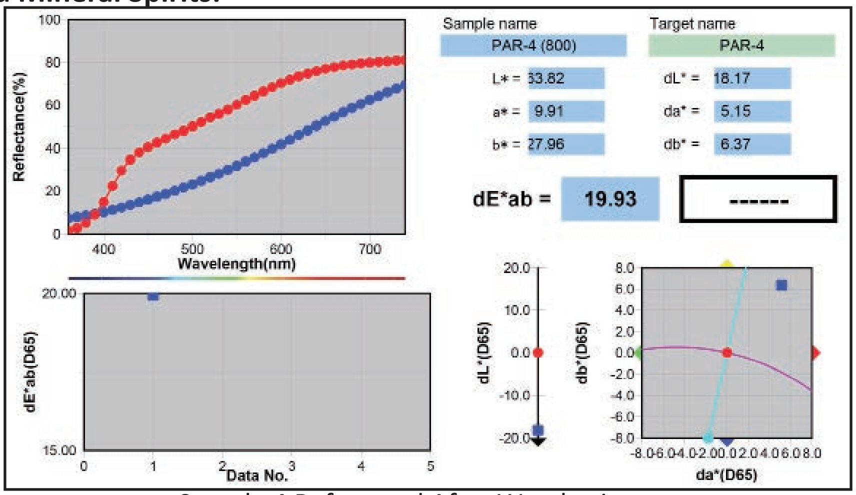
Sample 2 Before and After Weathering



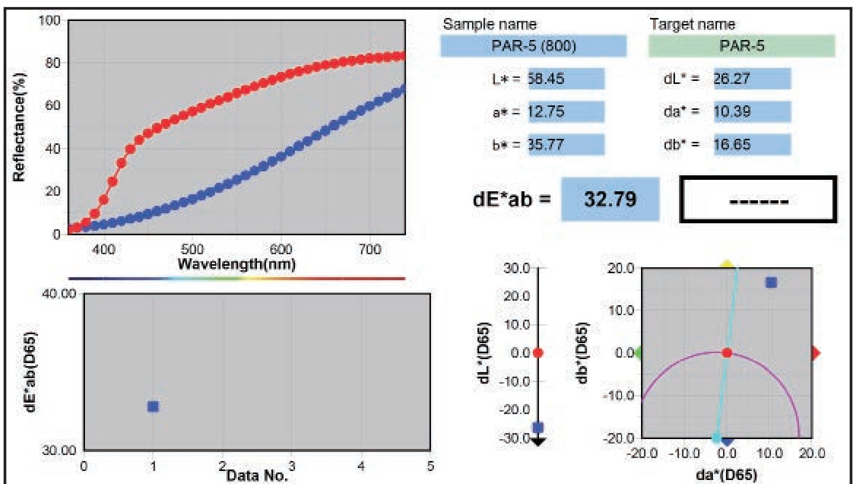
Sample 3 Before and After Weathering

Color Changes:

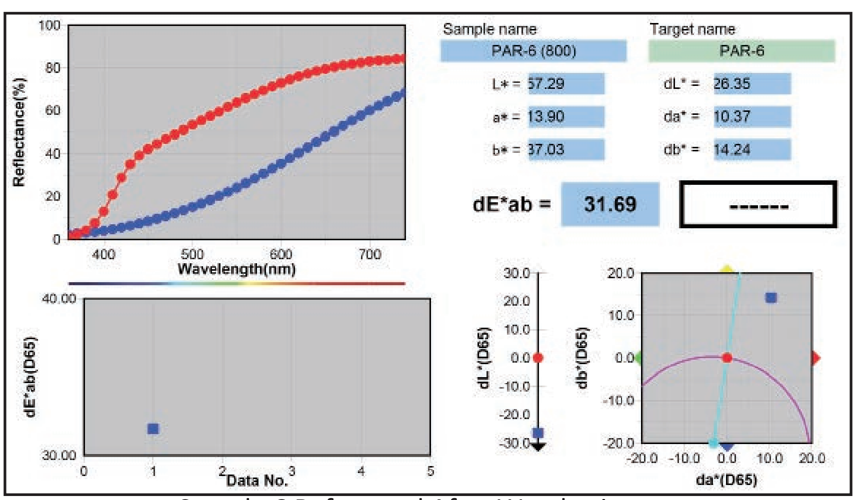
Paraffin and Mineral Spirits:



Sample 4 Before and After Weathering



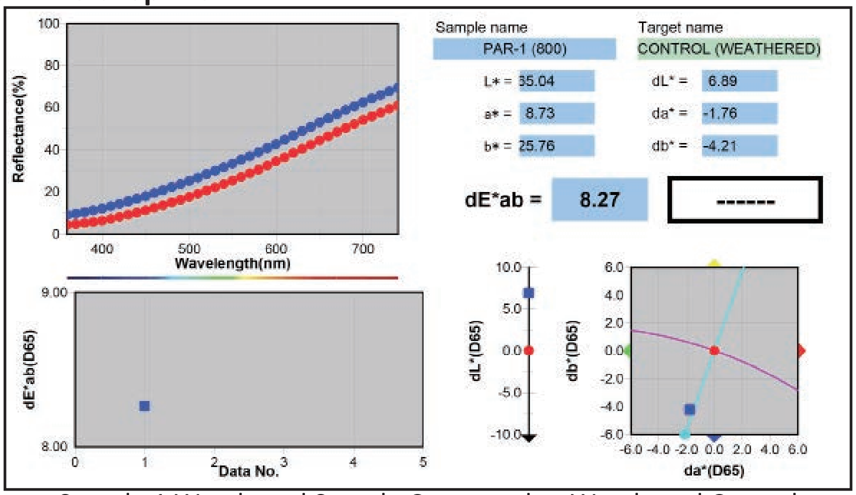
Sample 5 Before and After Weathering



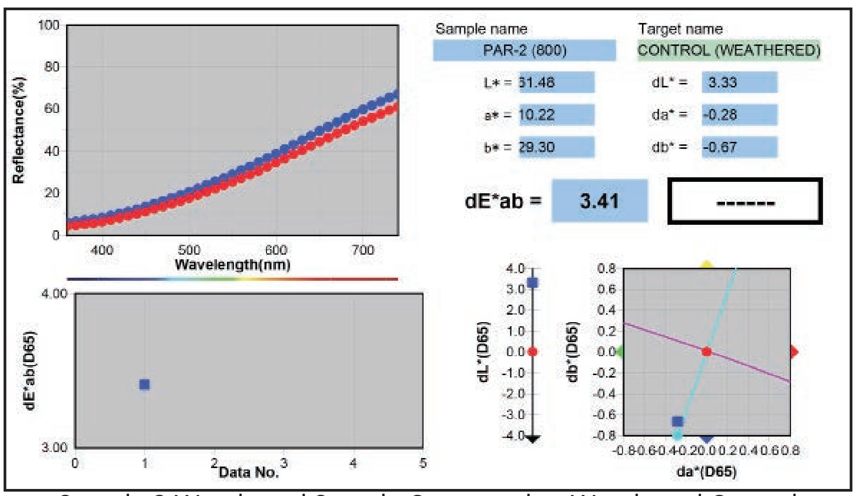
Sample 6 Before and After Weathering

Color Changes:

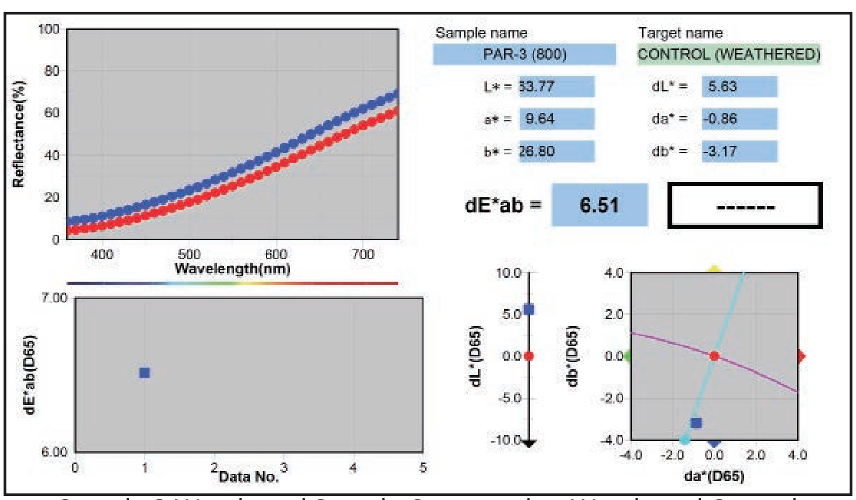
Paraffin and Mineral Spirits:



Sample 1 Weathered Sample Compared to Weathered Control



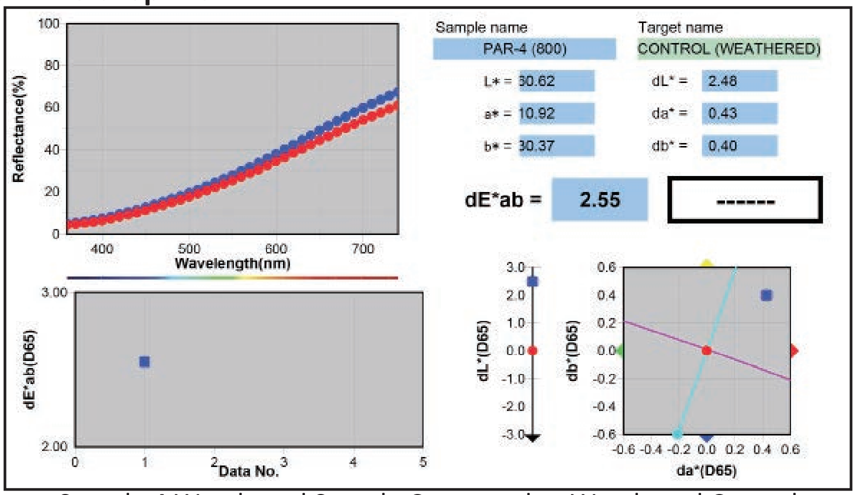
Sample 2 Weathered Sample Compared to Weathered Control



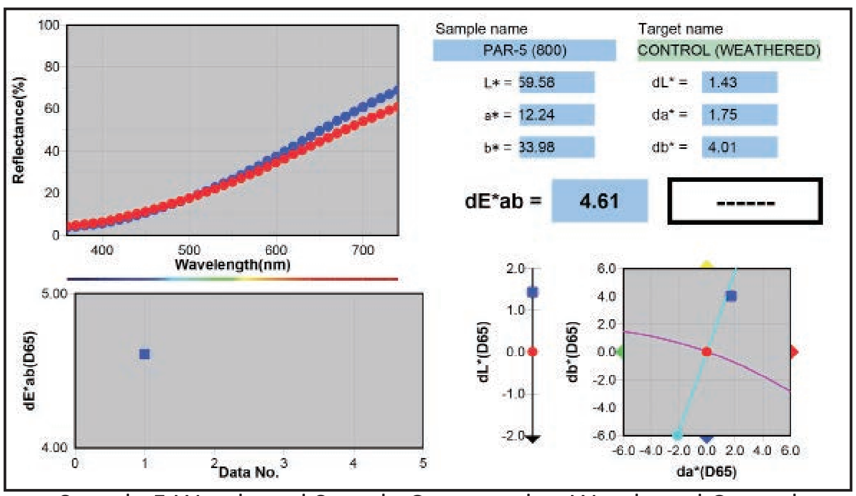
Sample 3 Weathered Sample Compared to Weathered Control

Color Changes:

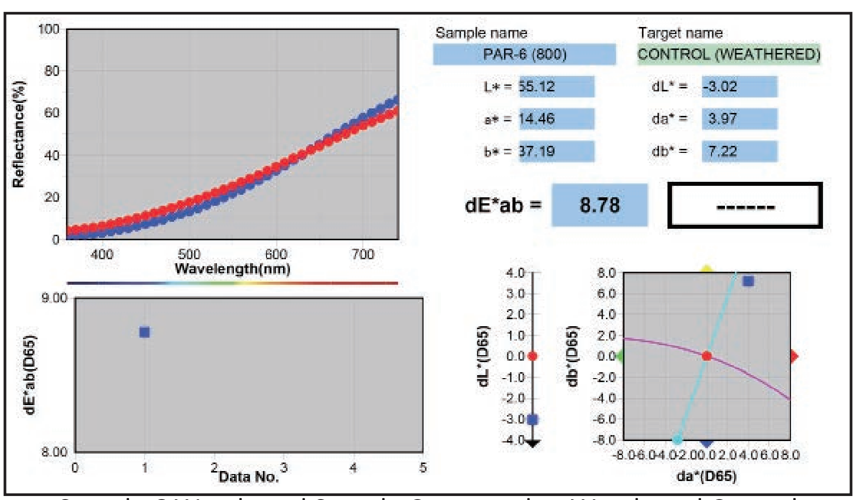
Paraffin and Mineral Spirits:



Sample 4 Weathered Sample Compared to Weathered Control



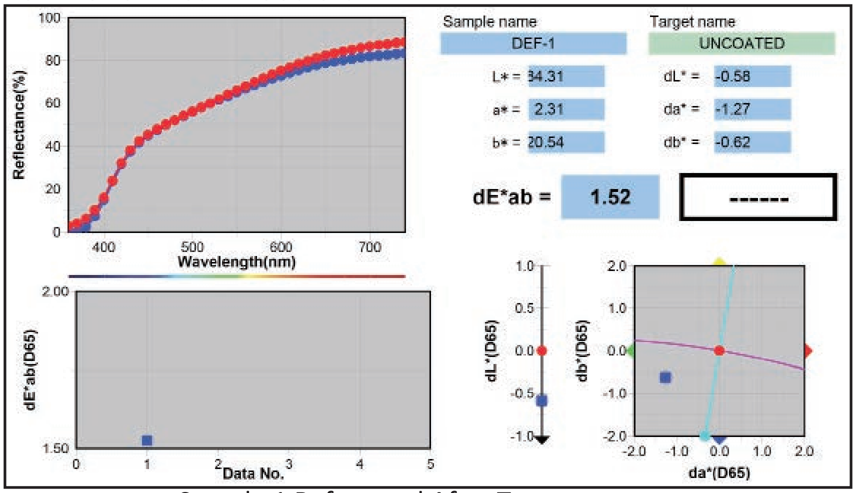
Sample 5 Weathered Sample Compared to Weathered Control



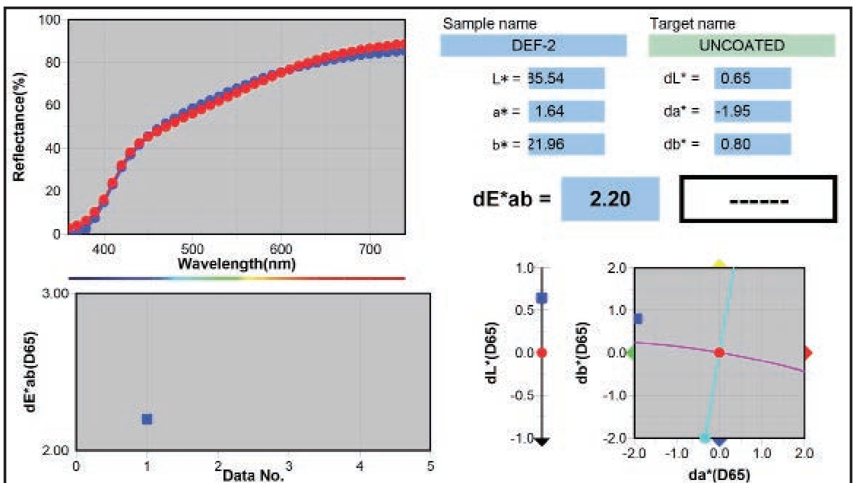
Sample 6 Weathered Sample Compared to Weathered Control

Color Changes:

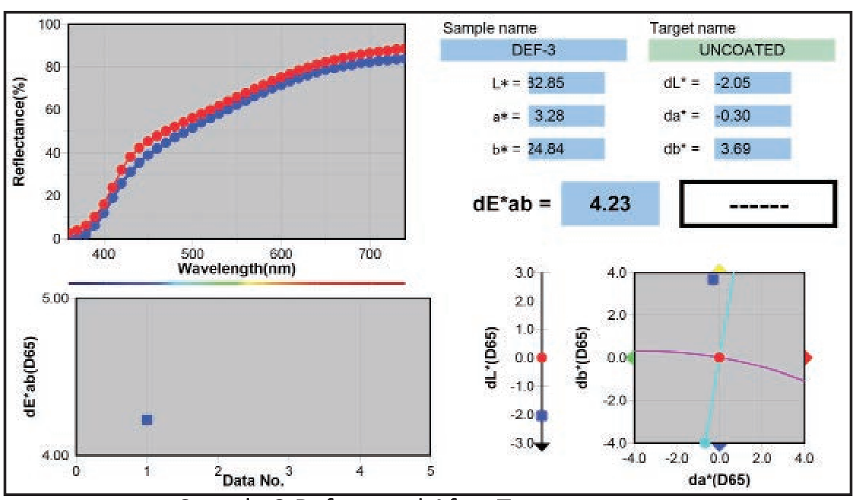
DEFY Extreme Exterior Clear Wood Stain:



Sample 1 Before and After Treatment



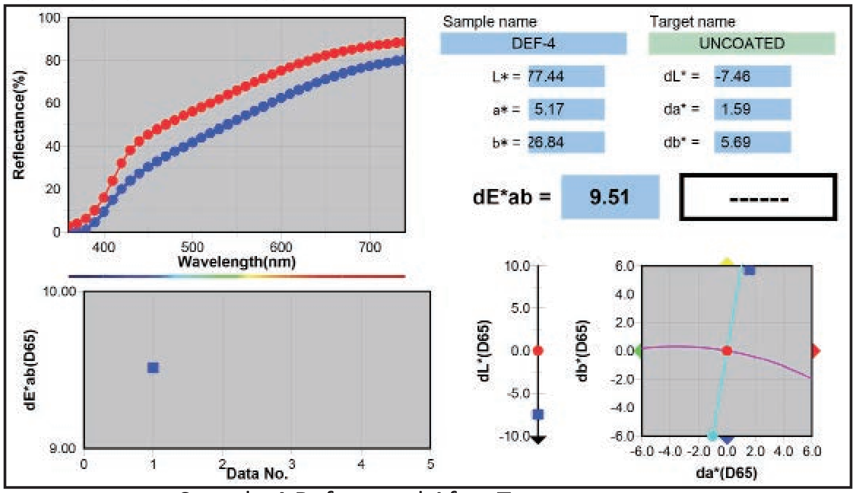
Sample 2 Before and After Treatment



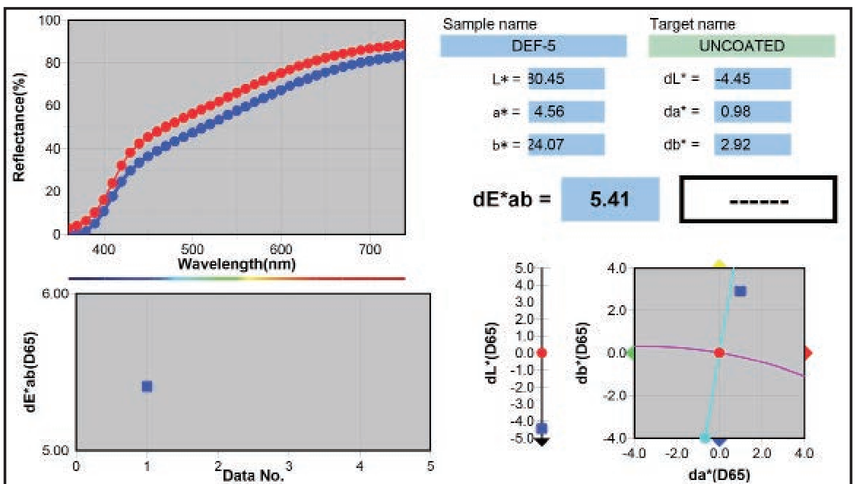
Sample 3 Before and After Treatment

Color Changes:

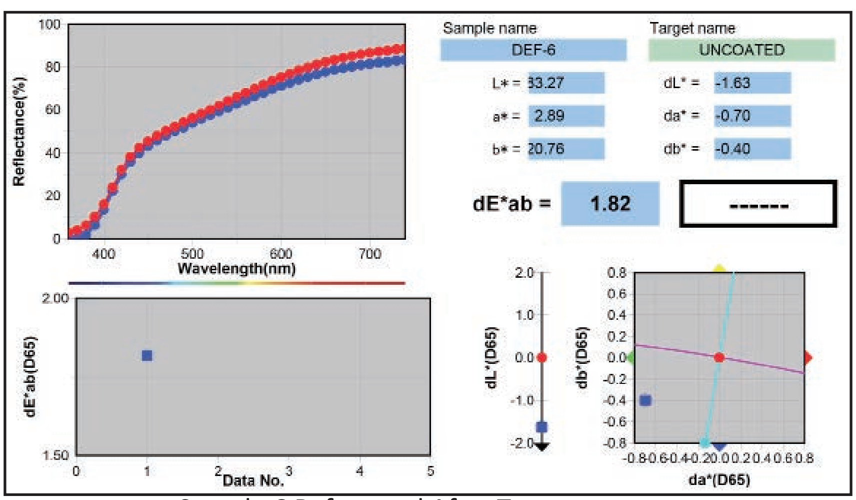
DEFY Extreme Exterior Clear Wood Stain:



Sample 4 Before and After Treatment



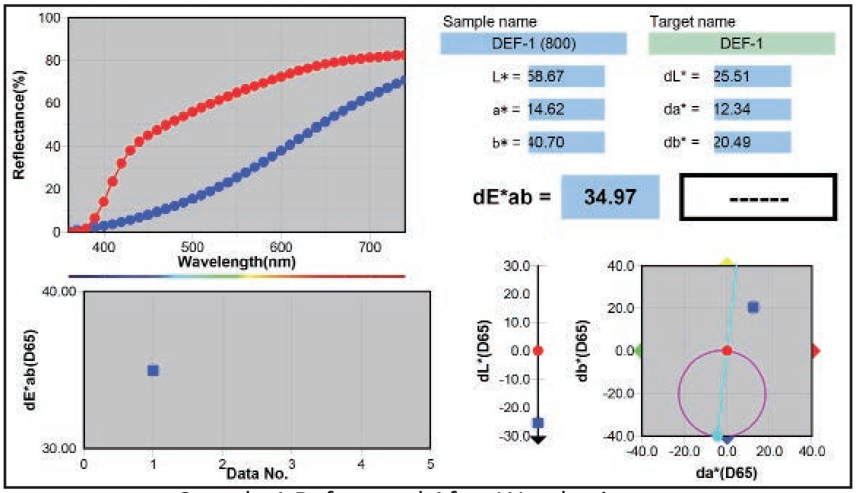
Sample 5 Before and After Treatment



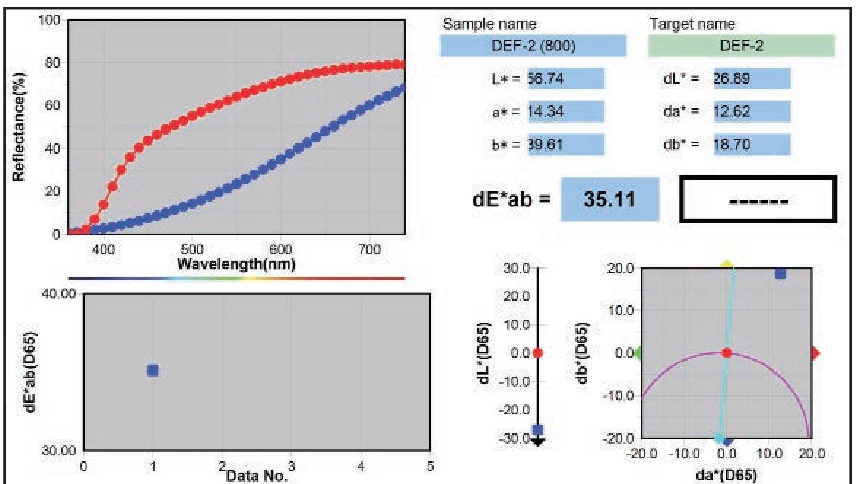
Sample 6 Before and After Treatment

Color Changes:

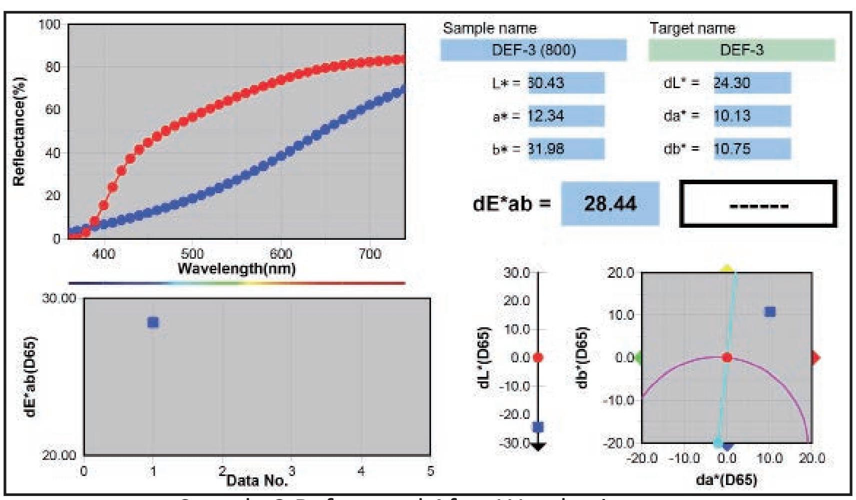
DEFY Extreme Exterior Clear Wood Stain:



Sample 1 Before and After Weathering



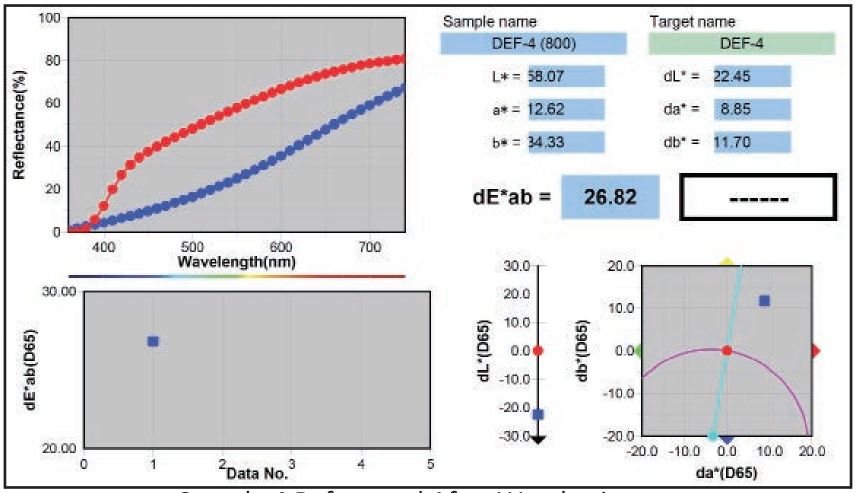
Sample 2 Before and After Weathering



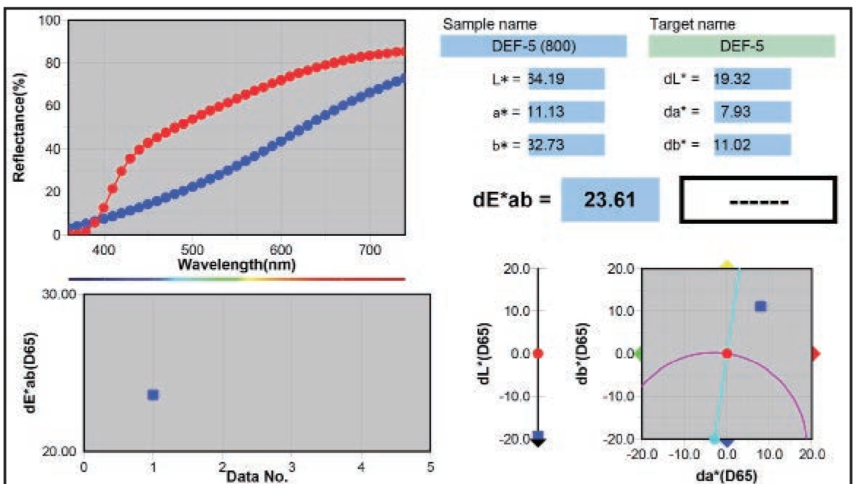
Sample 3 Before and After Weathering

Color Changes:

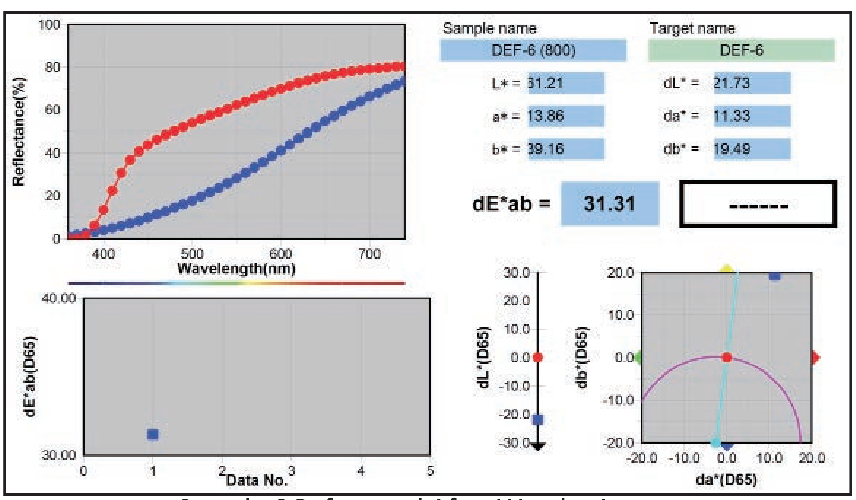
DEFY Extreme Exterior Clear Wood Stain:



Sample 4 Before and After Weathering



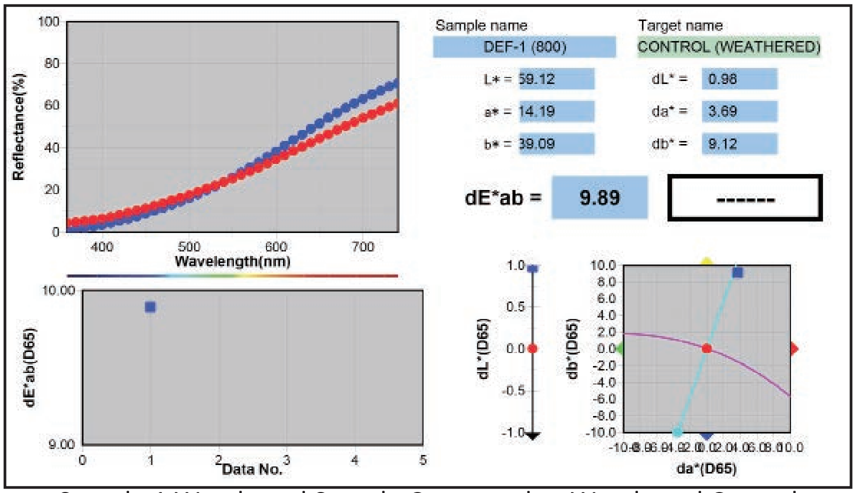
Sample 5 Before and After Weathering



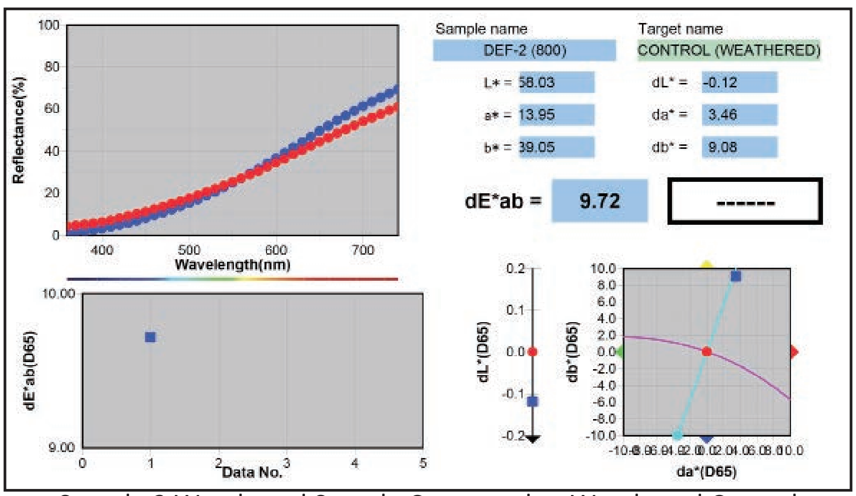
Sample 6 Before and After Weathering

Color Changes:

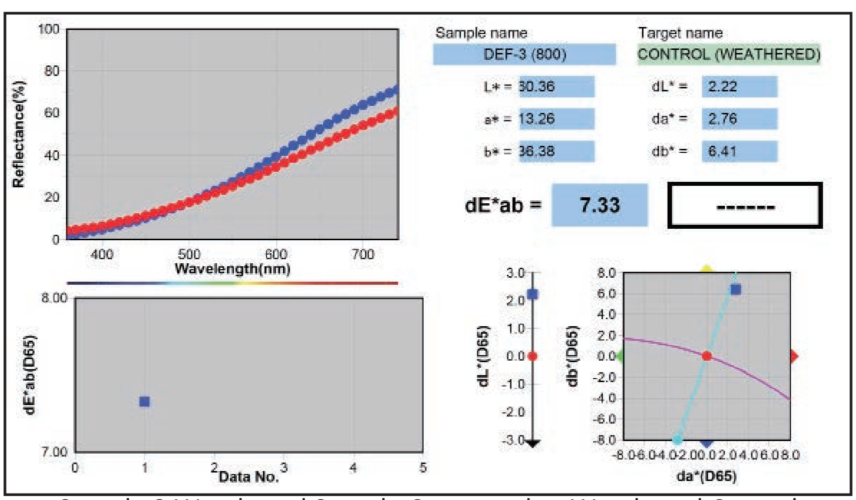
DEFY Extreme Exterior Clear Wood Stain:



Sample 1 Weathered Sample Compared to Weathered Control



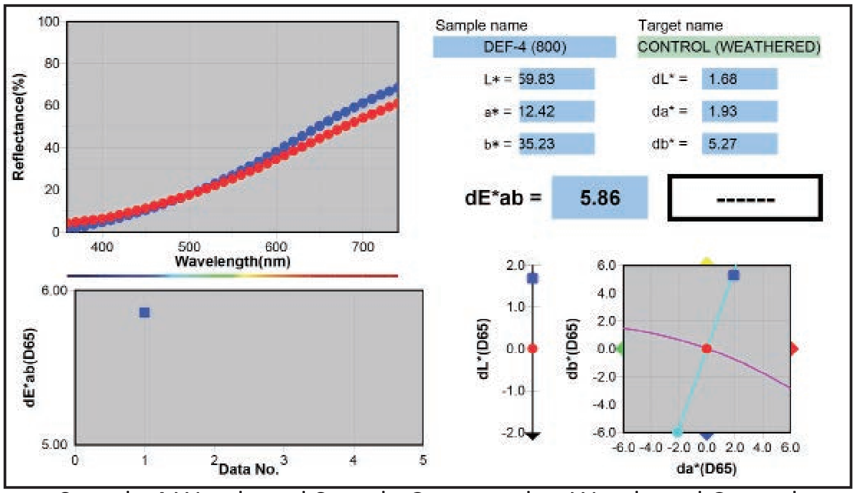
Sample 2 Weathered Sample Compared to Weathered Control



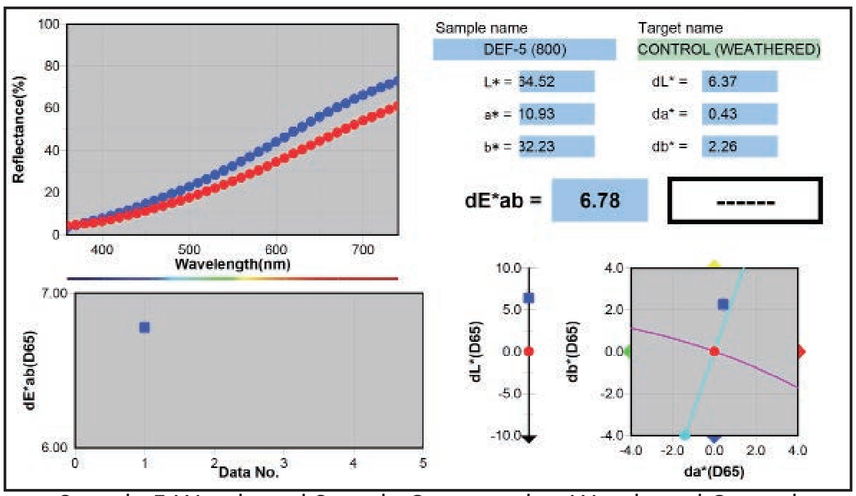
Sample 3 Weathered Sample Compared to Weathered Control

Color Changes:

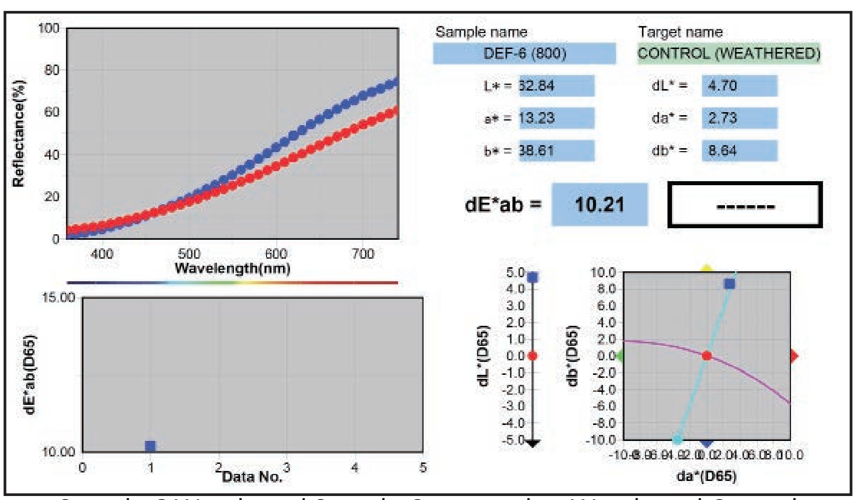
DEFY Extreme Exterior Clear Wood Stain:



Sample 4 Weathered Sample Compared to Weathered Control



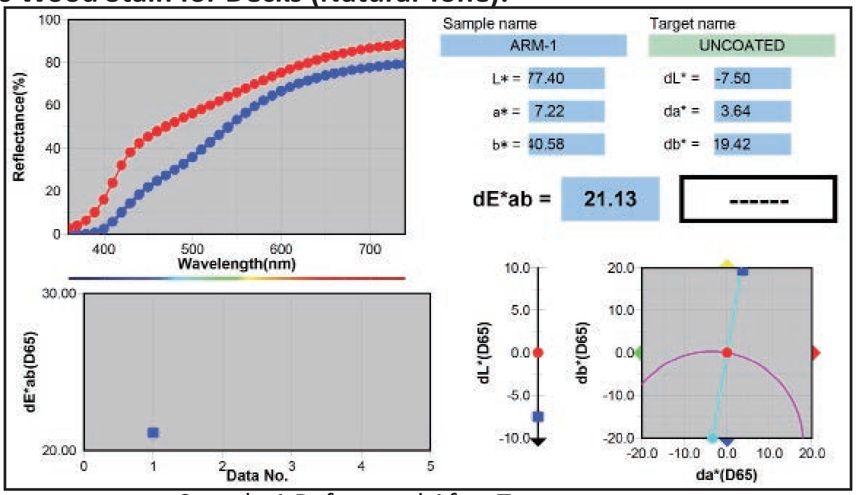
Sample 5 Weathered Sample Compared to Weathered Control



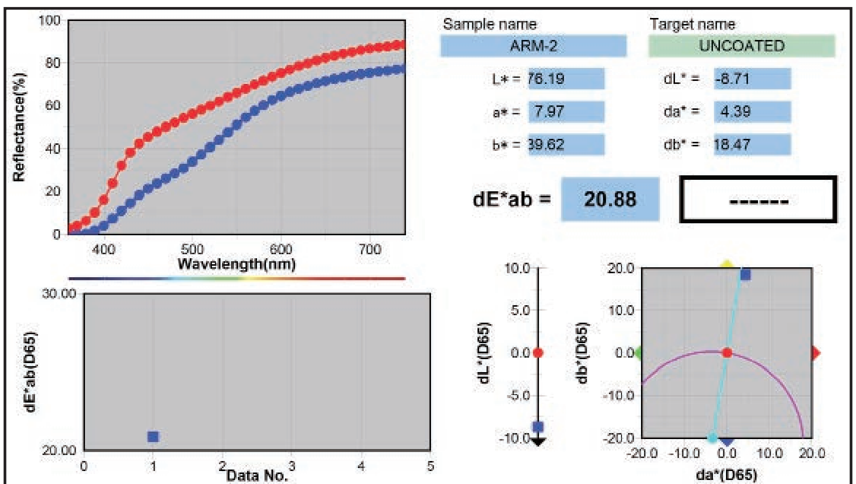
Sample 6 Weathered Sample Compared to Weathered Control

Color Changes:

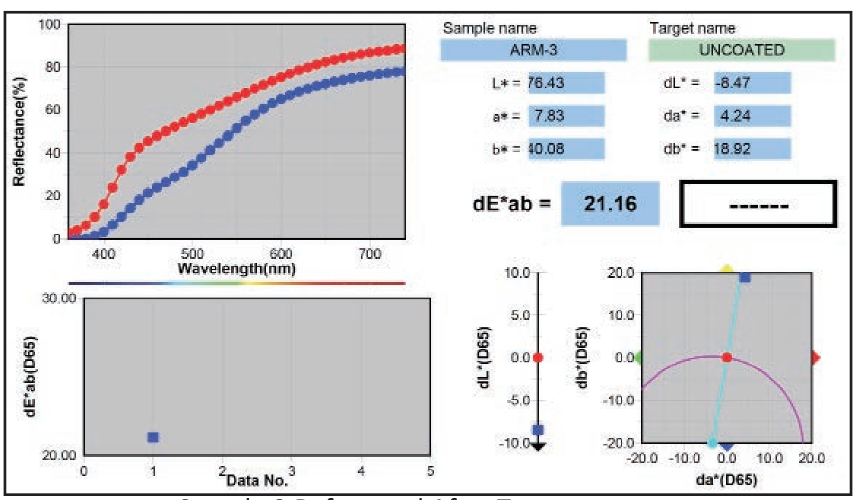
Armstrong's Wood Stain for Decks (Natural Tone):



Sample 1 Before and After Treatment



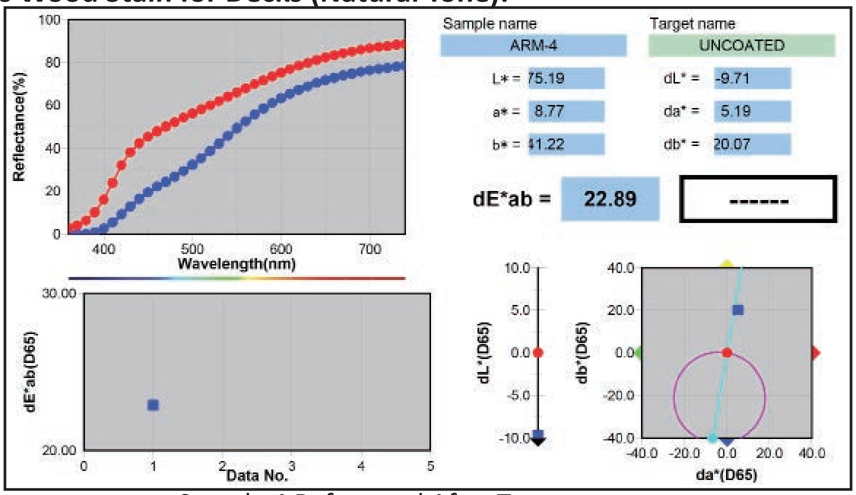
Sample 2 Before and After Treatment



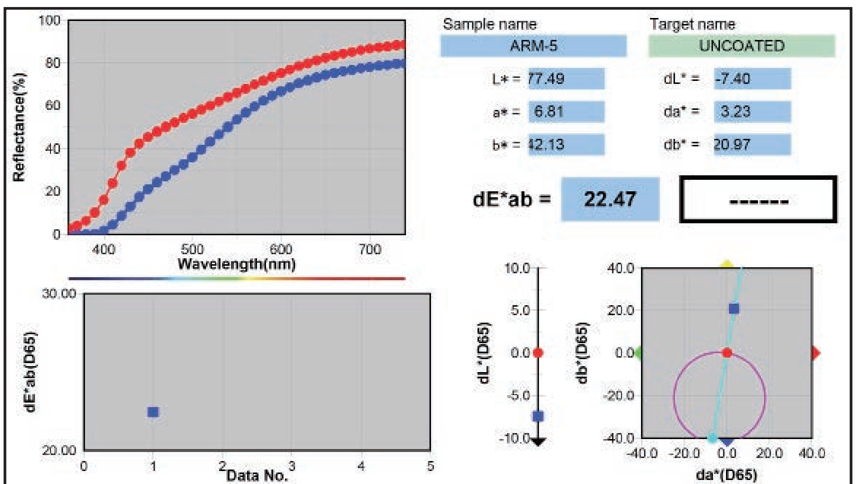
Sample 3 Before and After Treatment

Color Changes:

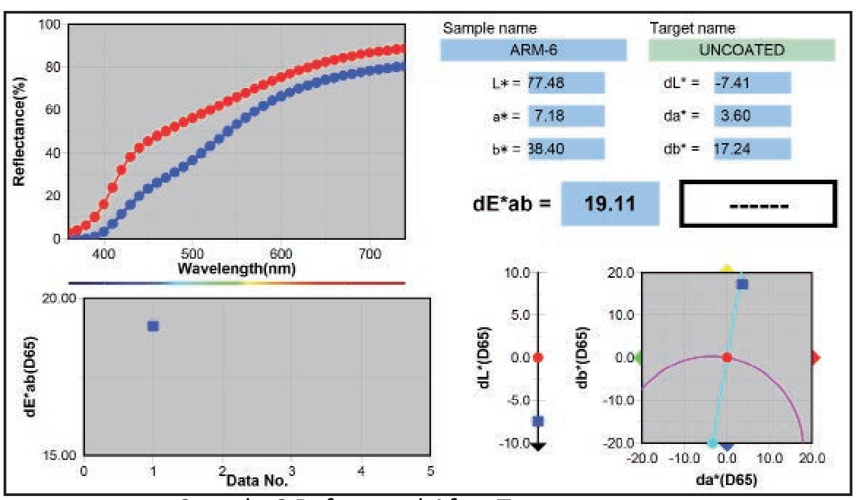
Armstrong's Wood Stain for Decks (Natural Tone):



Sample 4 Before and After Treatment



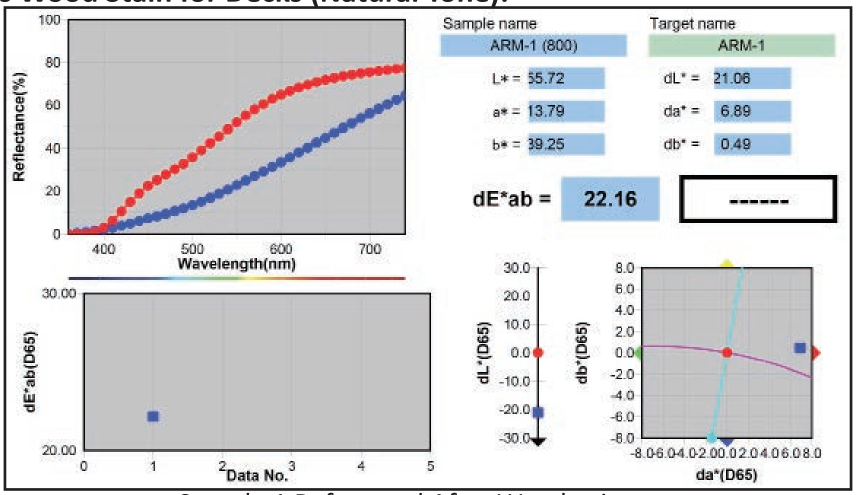
Sample 5 Before and After Treatment



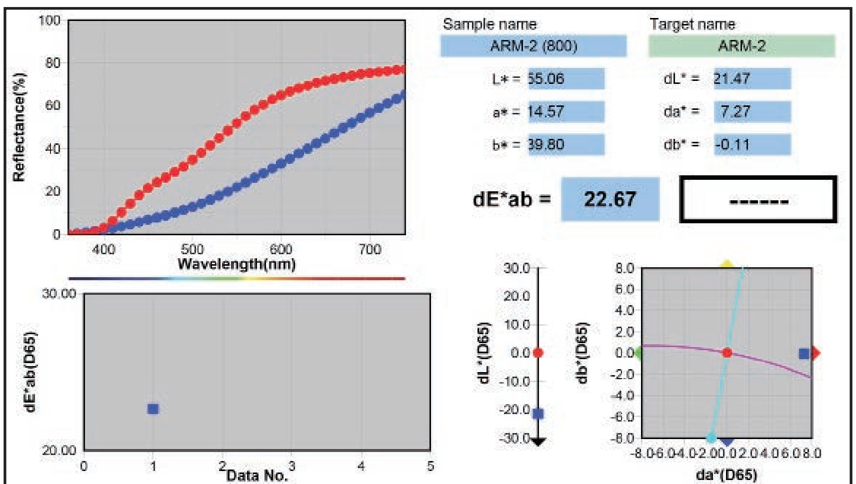
Sample 6 Before and After Treatment

Color Changes:

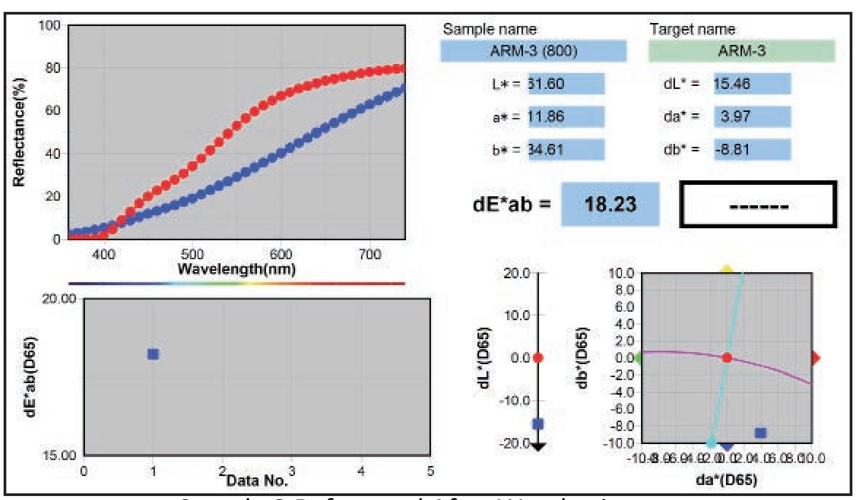
Armstrong's Wood Stain for Decks (Natural Tone):



Sample 1 Before and After Weathering



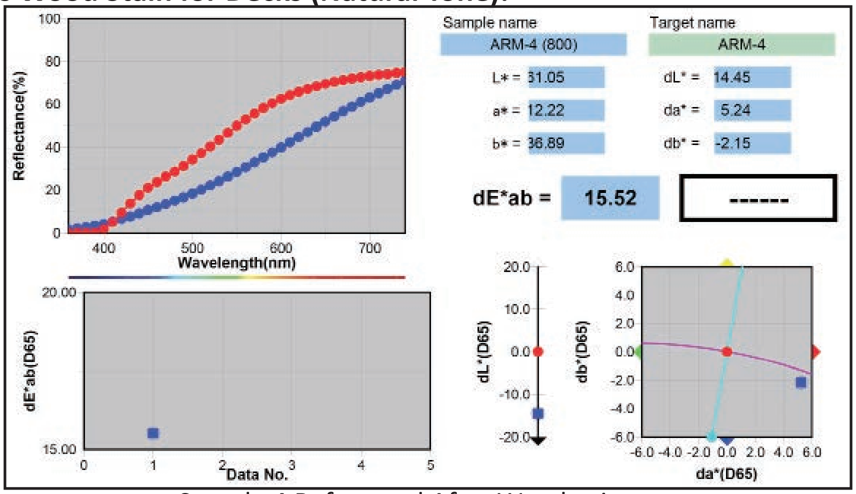
Sample 2 Before and After Weathering



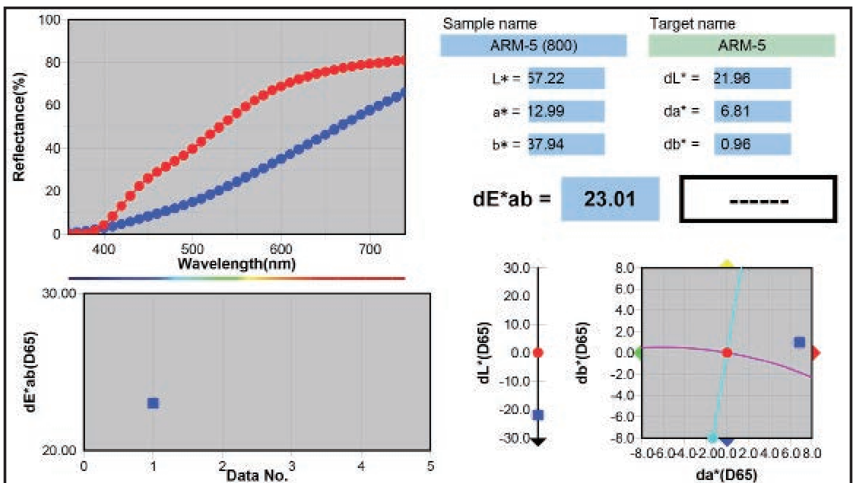
Sample 3 Before and After Weathering

Color Changes:

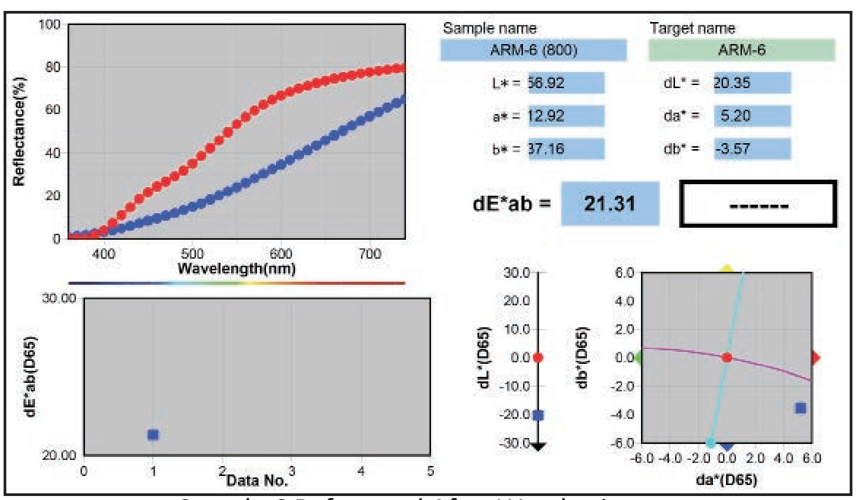
Armstrong's Wood Stain for Decks (Natural Tone):



Sample 4 Before and After Weathering



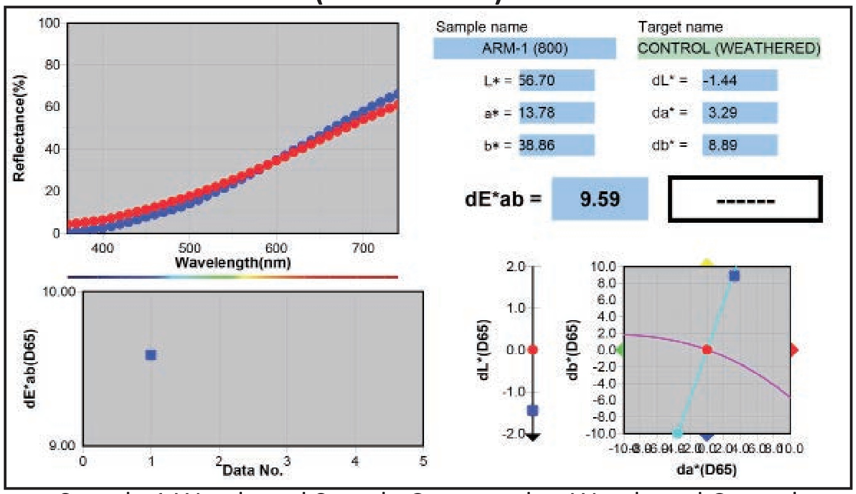
Sample 5 Before and After Weathering



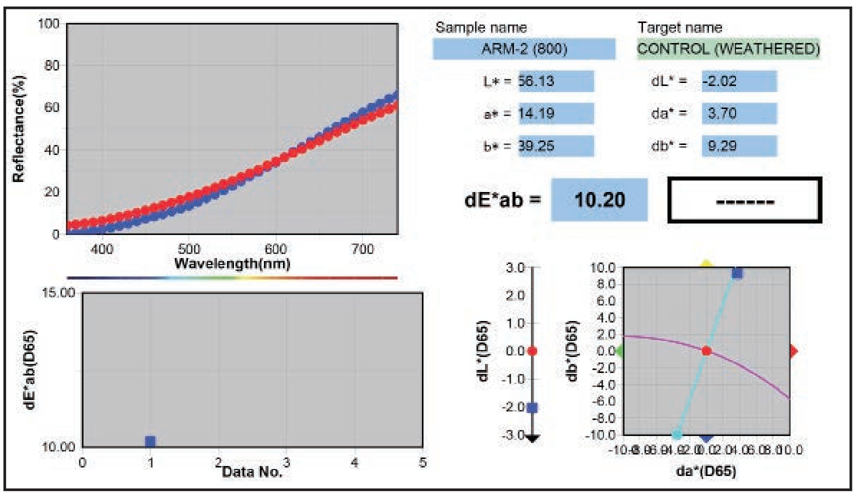
Sample 6 Before and After Weathering

Color Changes:

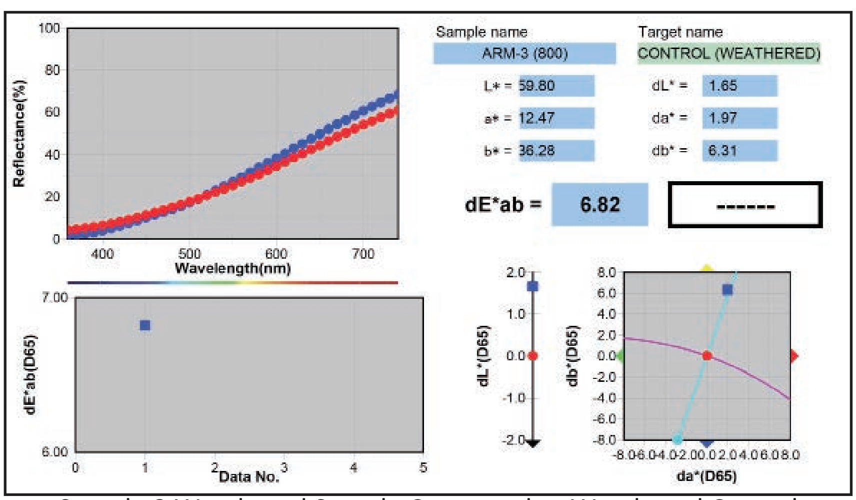
Armstrong's Wood Stain for Decks (Natural Tone):



Sample 1 Weathered Sample Compared to Weathered Control



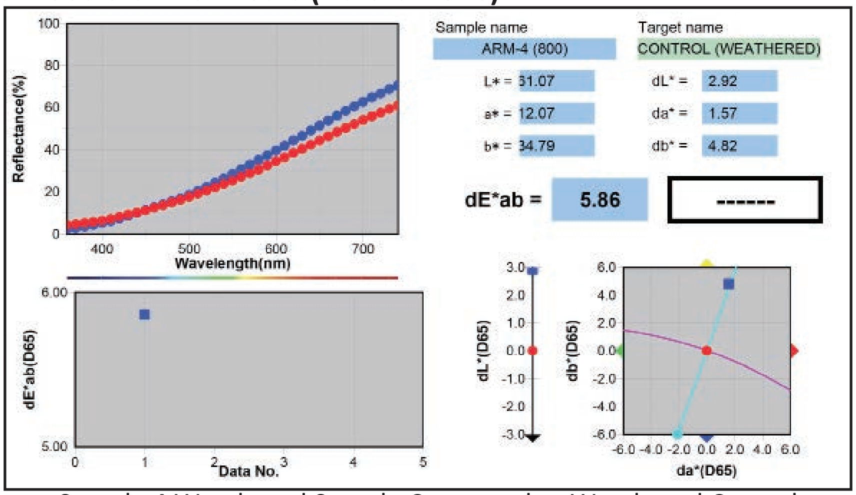
Sample 2 Weathered Sample Compared to Weathered Control



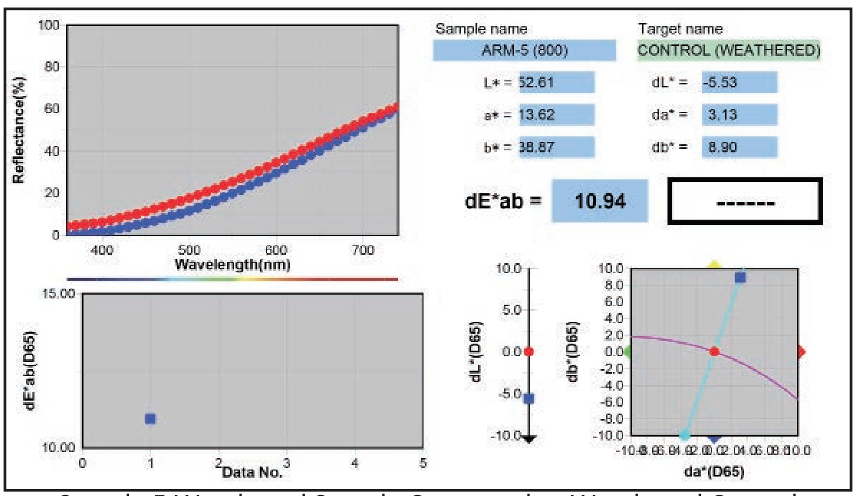
Sample 3 Weathered Sample Compared to Weathered Control

Color Changes:

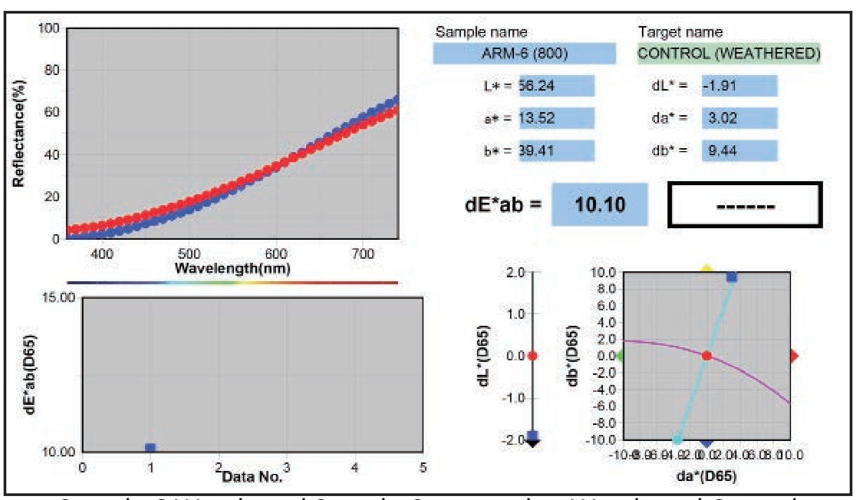
Armstrong's Wood Stain for Decks (Natural Tone):



Sample 4 Weathered Sample Compared to Weathered Control



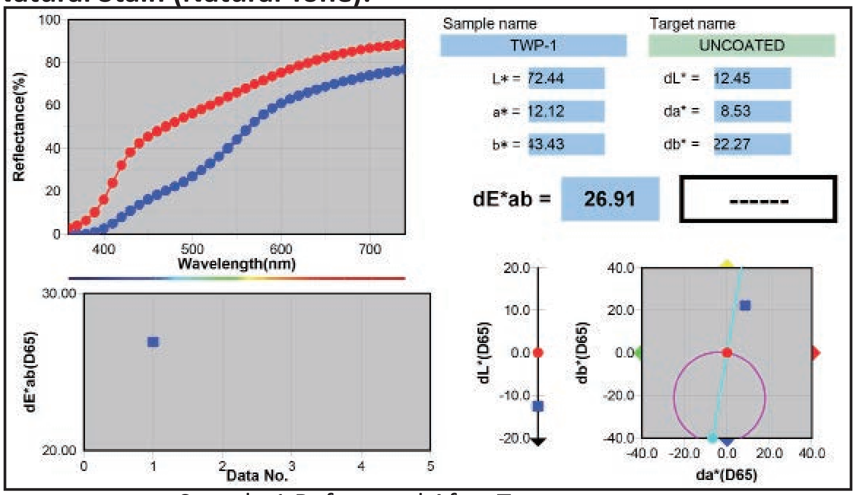
Sample 5 Weathered Sample Compared to Weathered Control



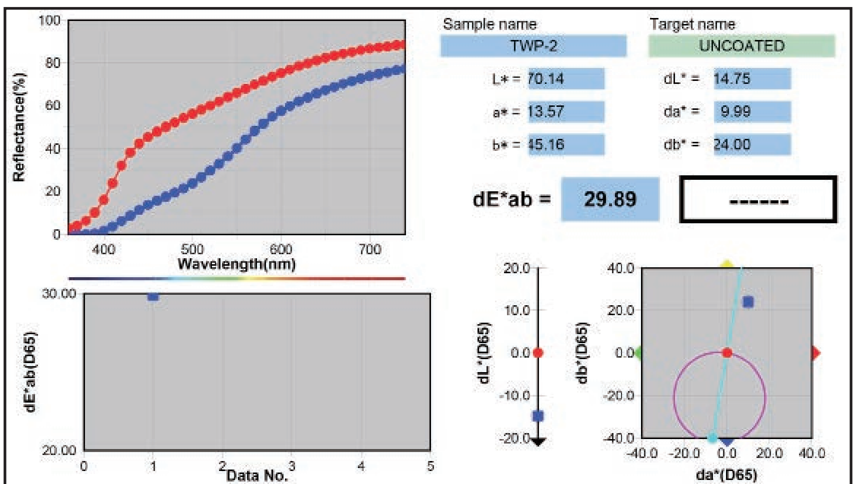
Sample 6 Weathered Sample Compared to Weathered Control

Color Changes:

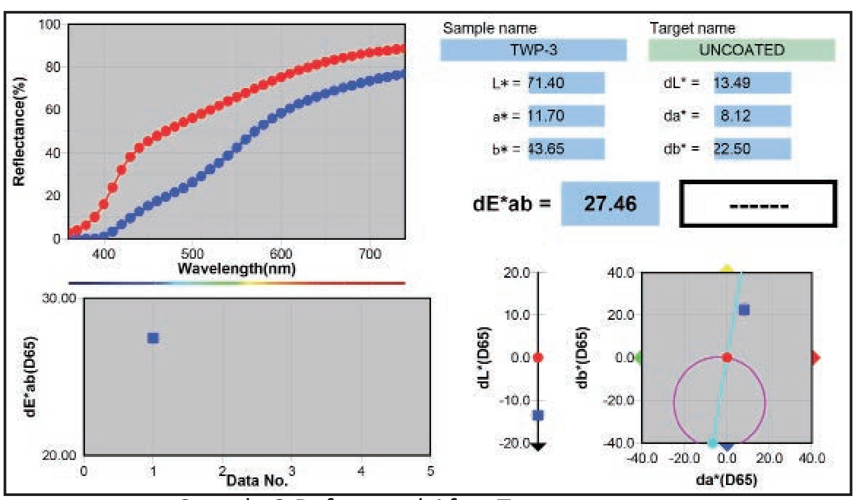
TWP 1500 Natural Stain (Natural Tone):



Sample 1 Before and After Treatment



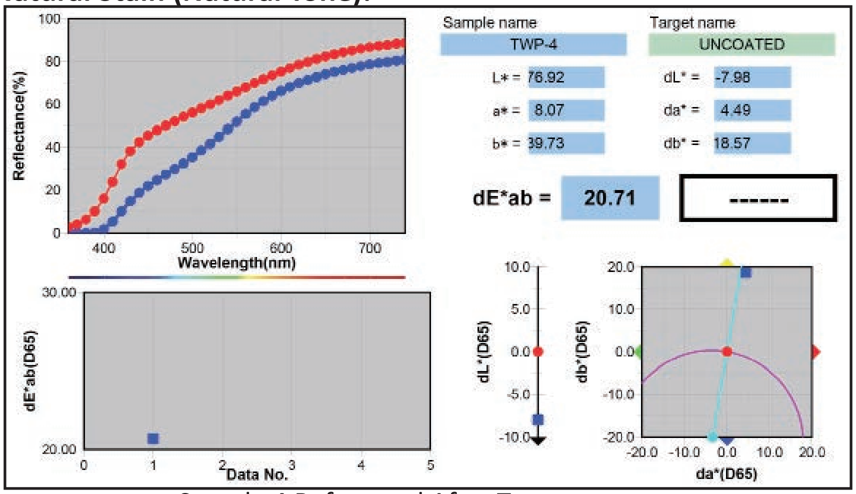
Sample 2 Before and After Treatment



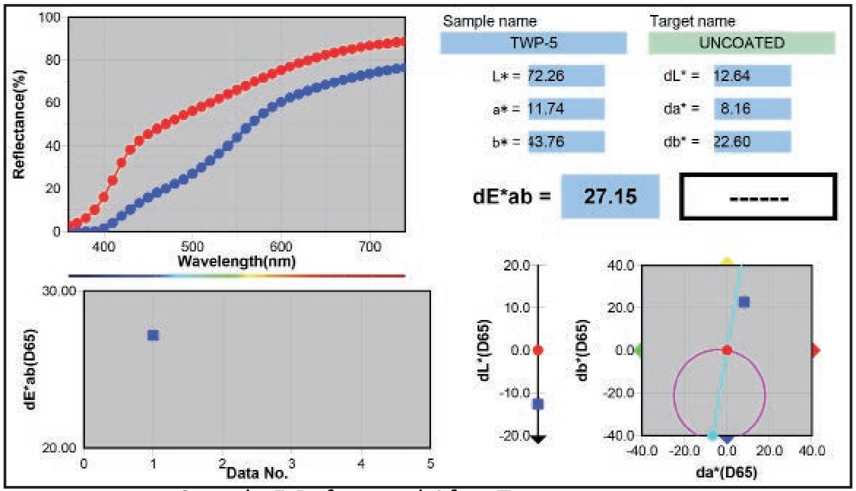
Sample 3 Before and After Treatment

Color Changes:

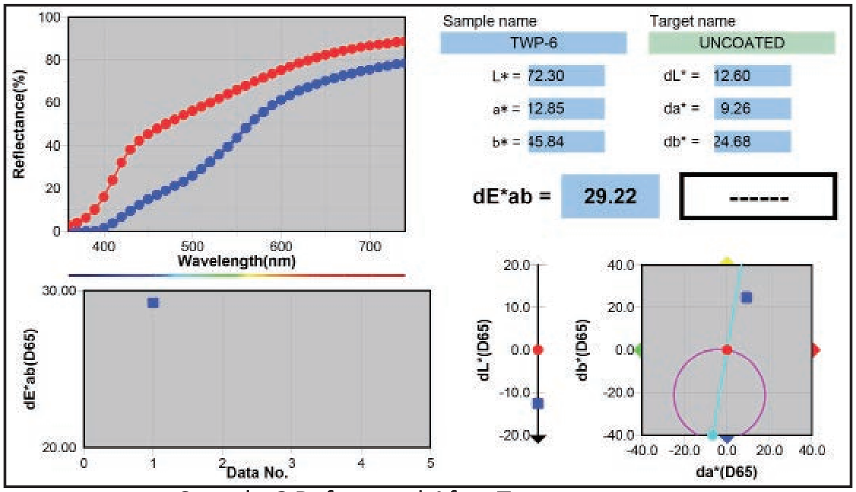
TWP 1500 Natural Stain (Natural Tone):



Sample 4 Before and After Treatment



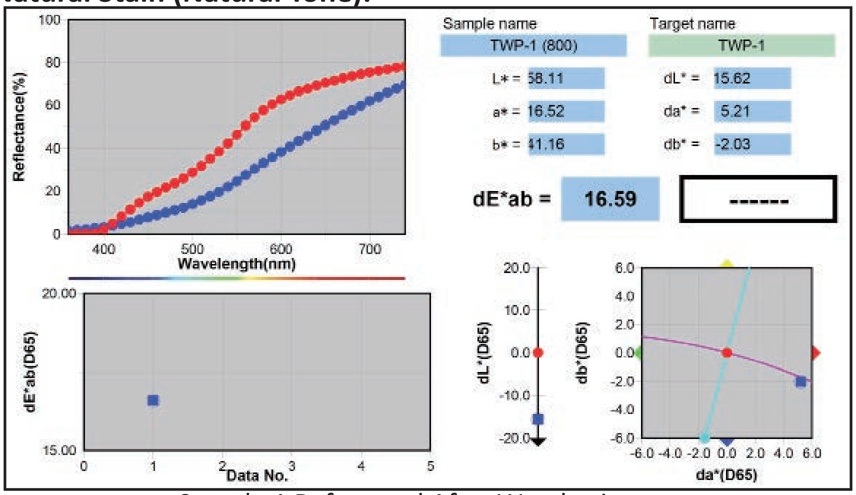
Sample 5 Before and After Treatment



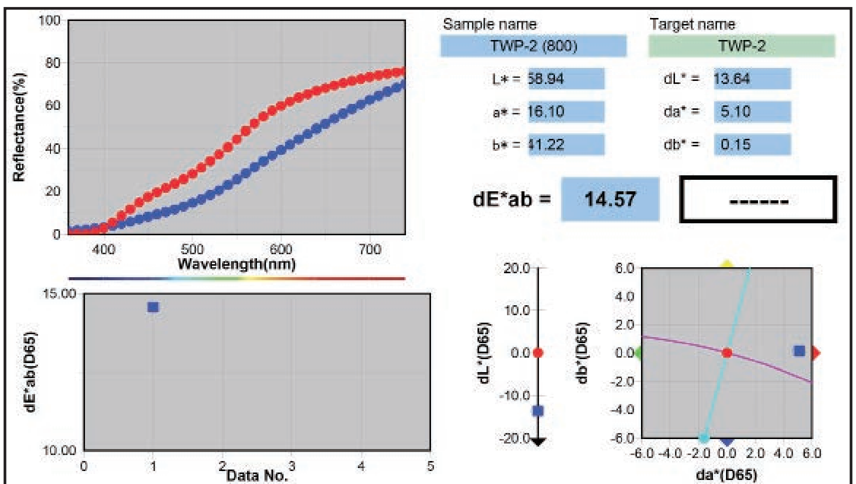
Sample 6 Before and After Treatment

Color Changes:

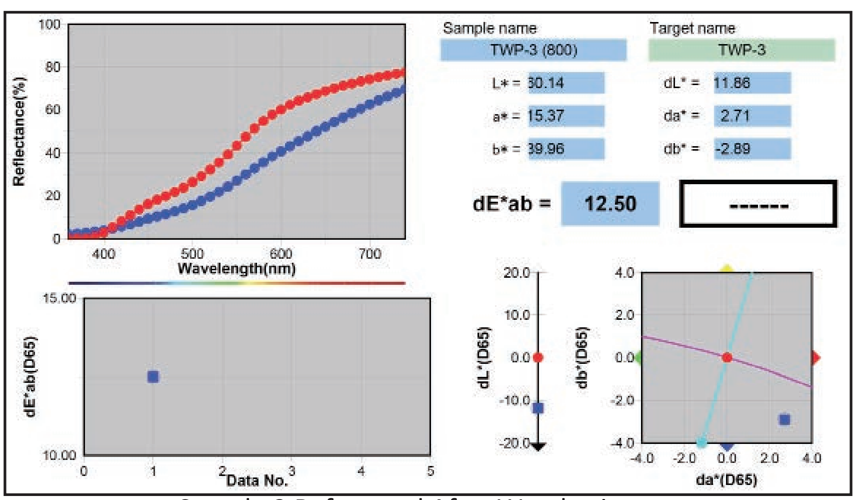
TWP 1500 Natural Stain (Natural Tone):



Sample 1 Before and After Weathering



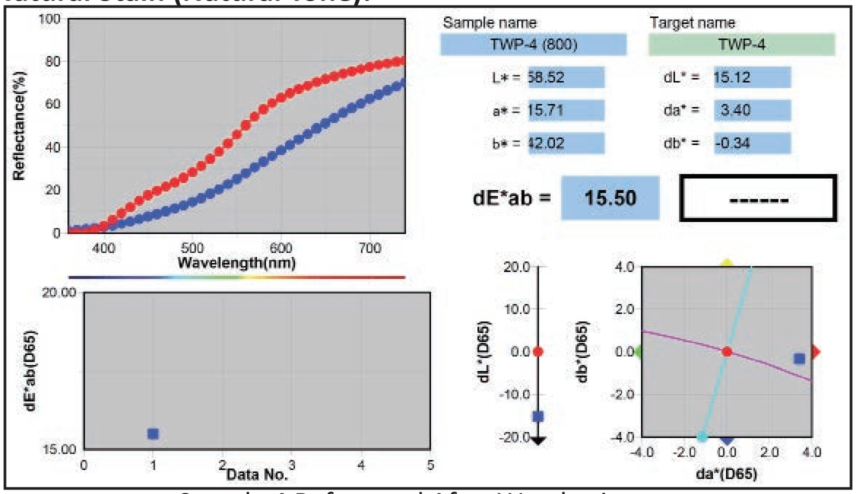
Sample 2 Before and After Weathering



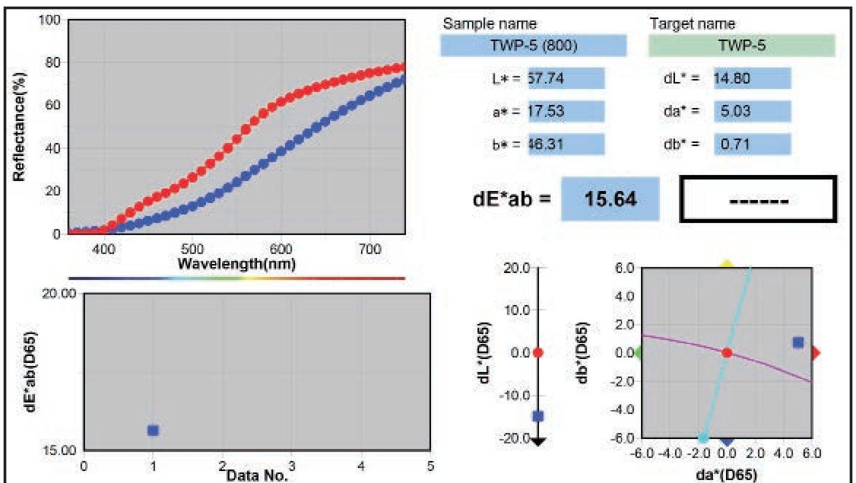
Sample 3 Before and After Weathering

Color Changes:

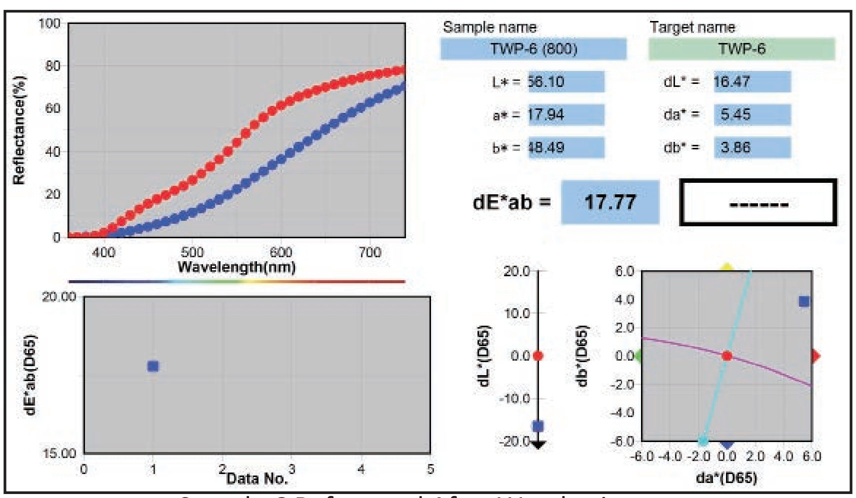
TWP 1500 Natural Stain (Natural Tone):



Sample 4 Before and After Weathering



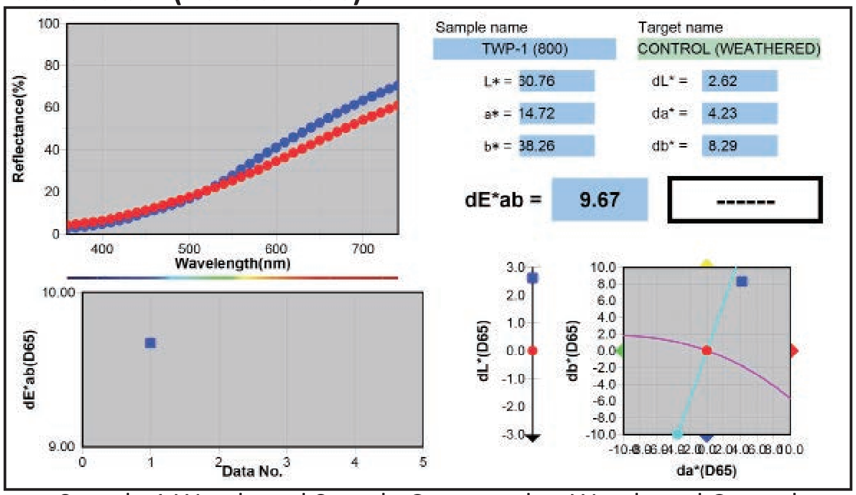
Sample 5 Before and After Weathering



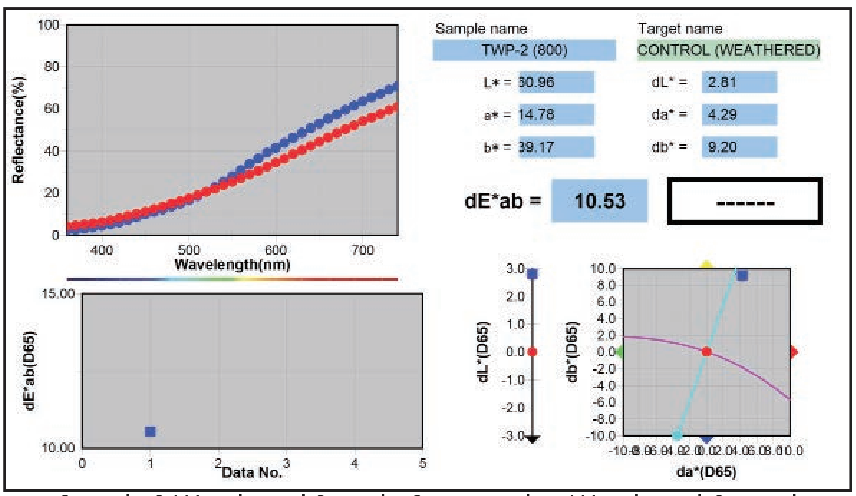
Sample 6 Before and After Weathering

Color Changes:

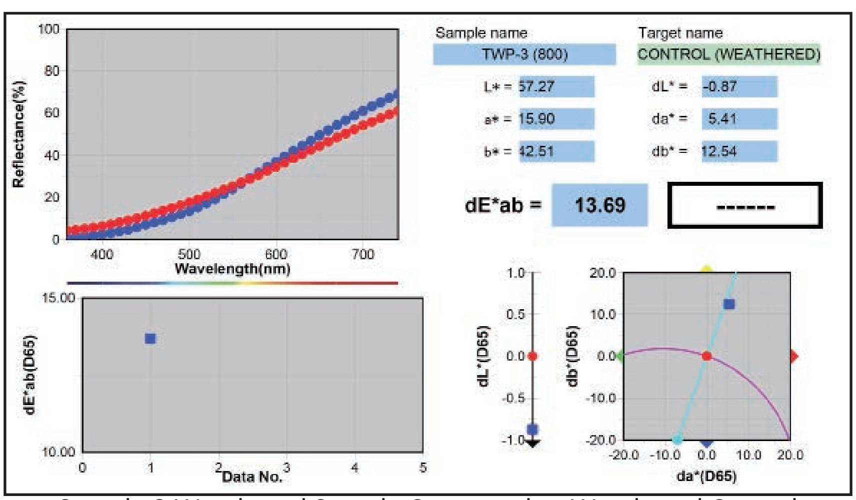
TWP 1500 Natural Stain (Natural Tone):



Sample 1 Weathered Sample Compared to Weathered Control



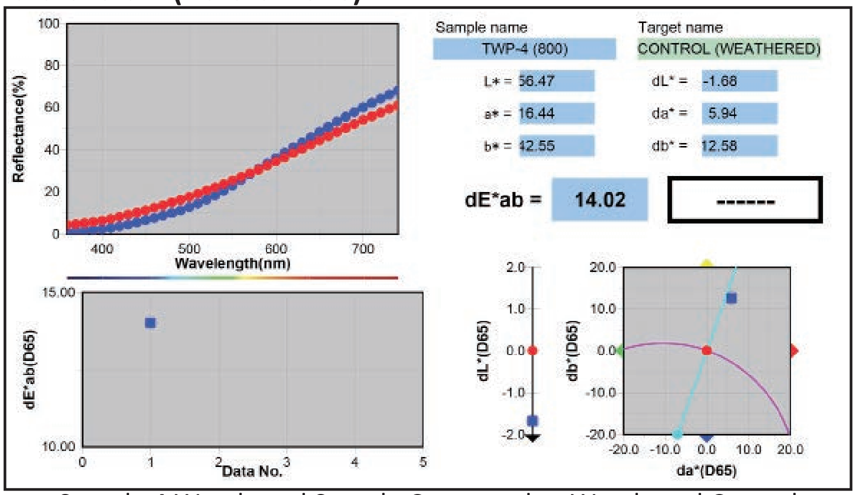
Sample 2 Weathered Sample Compared to Weathered Control



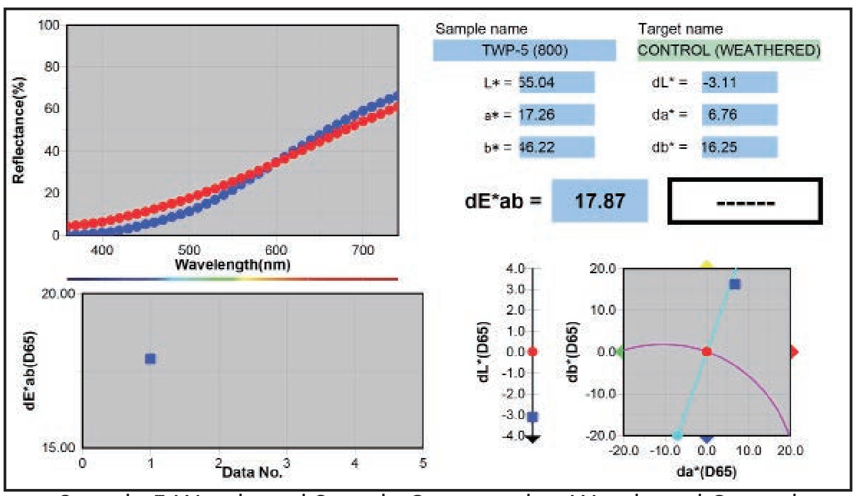
Sample 3 Weathered Sample Compared to Weathered Control

Color Changes:

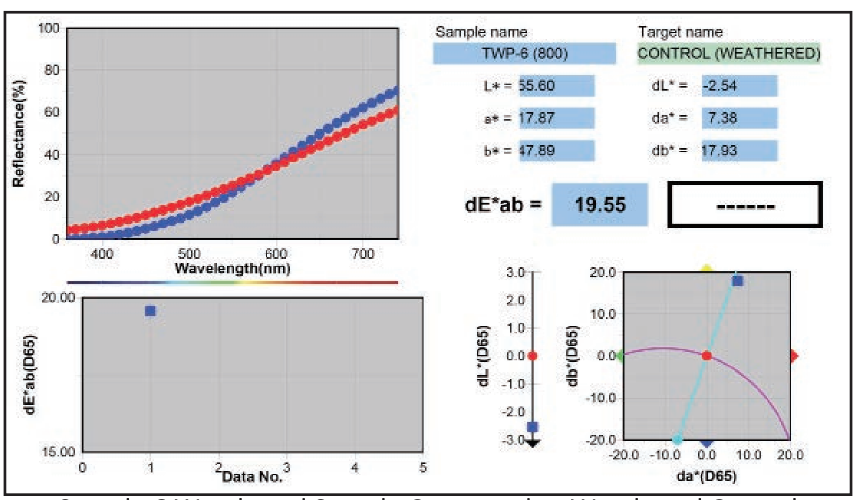
TWP 1500 Natural Stain (Natural Tone):



Sample 4 Weathered Sample Compared to Weathered Control



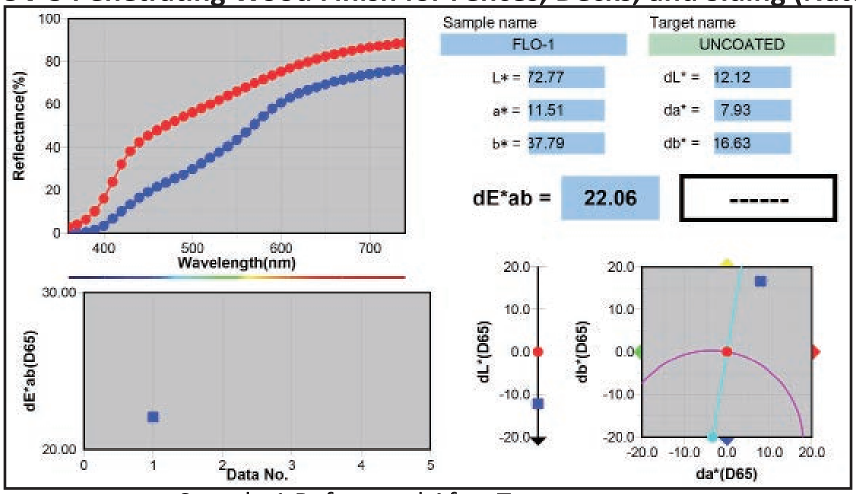
Sample 5 Weathered Sample Compared to Weathered Control



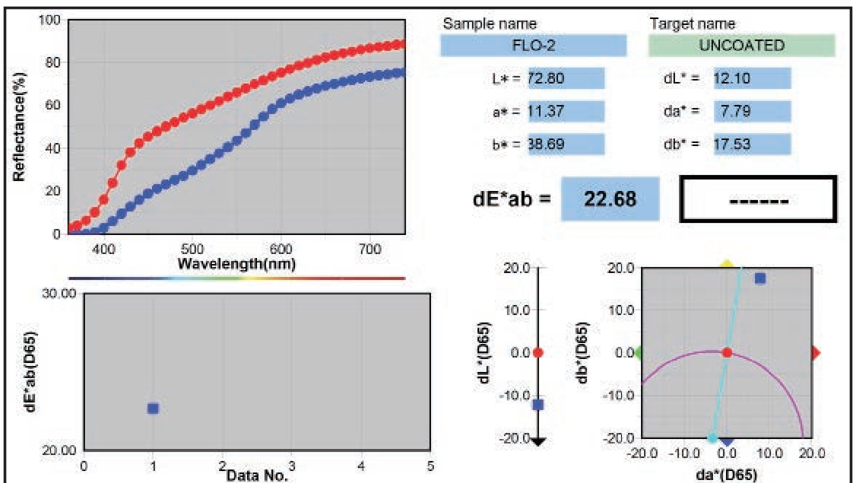
Sample 6 Weathered Sample Compared to Weathered Control

Color Changes:

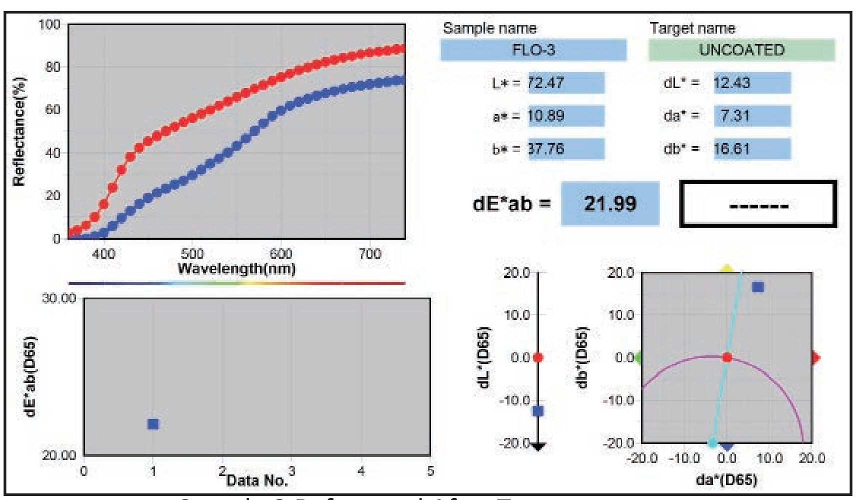
Flood CWF UV-5 Penetrating Wood Finish for Fences, Decks, and Siding (Natural Tone (Clear)):



Sample 1 Before and After Treatment



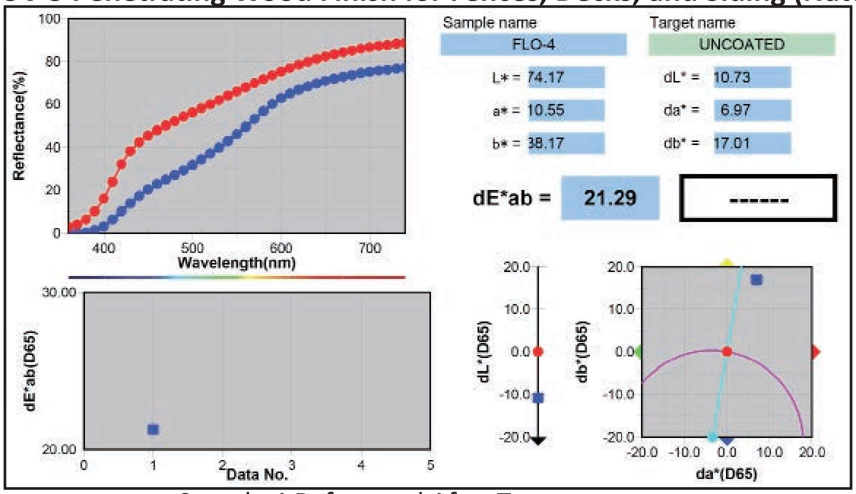
Sample 2 Before and After Treatment



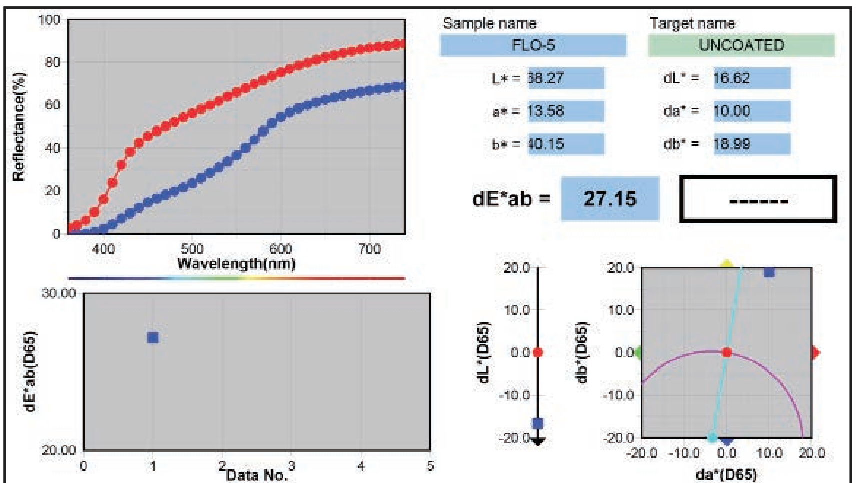
Sample 3 Before and After Treatment

Color Changes:

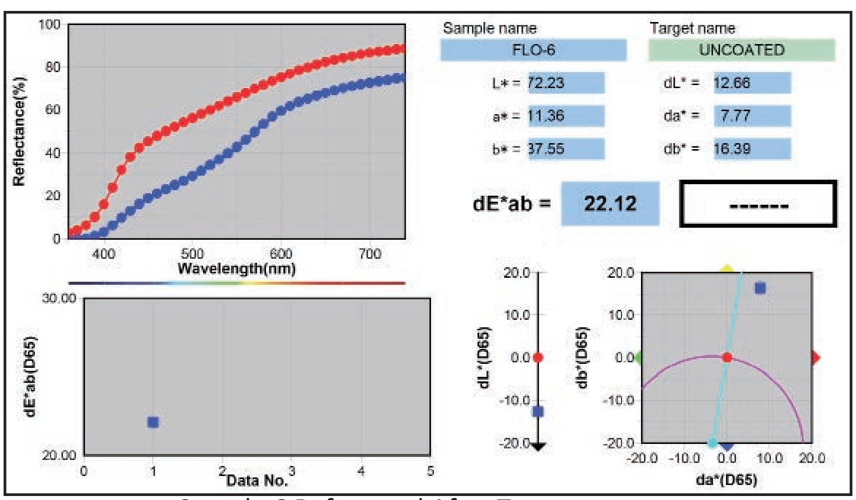
Flood CWF UV-5 Penetrating Wood Finish for Fences, Decks, and Siding (Natural Tone (Clear)):



Sample 4 Before and After Treatment



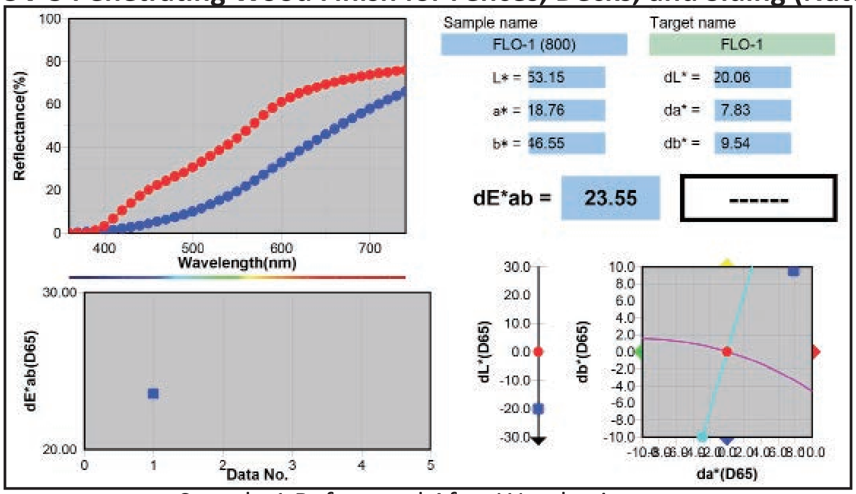
Sample 5 Before and After Treatment



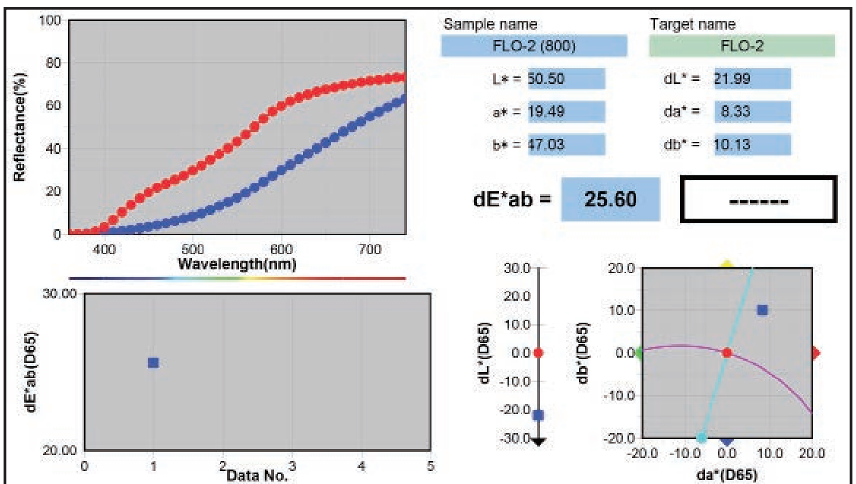
Sample 6 Before and After Treatment

Color Changes:

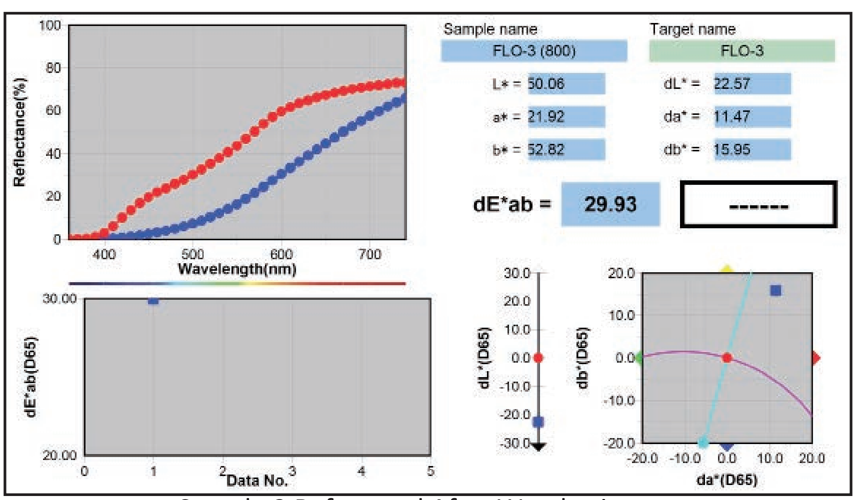
Flood CWF UV-5 Penetrating Wood Finish for Fences, Decks, and Siding (Natural Tone (Clear)):



Sample 1 Before and After Weathering



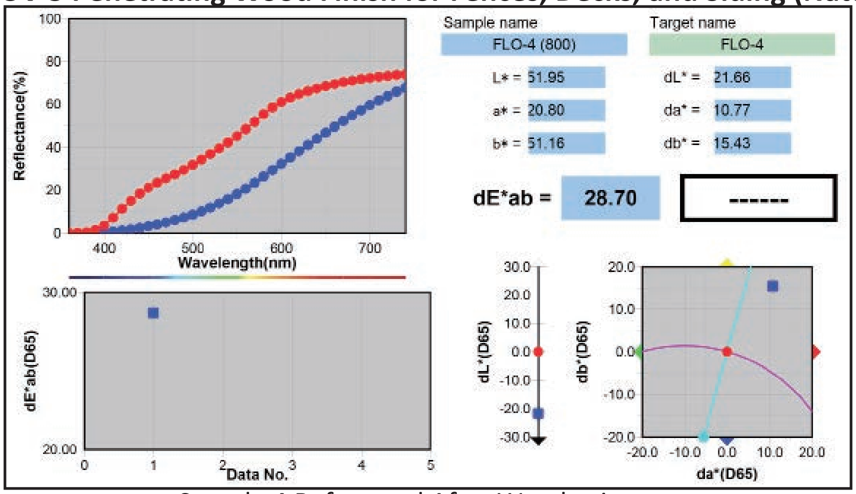
Sample 2 Before and After Weathering



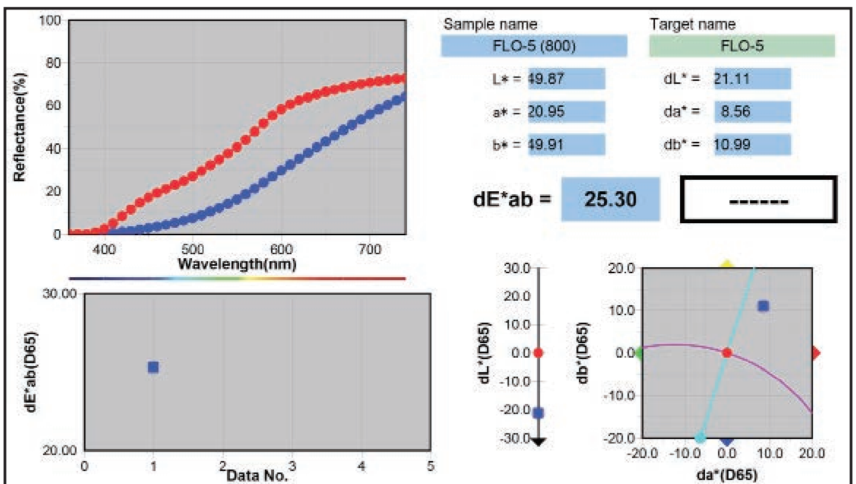
Sample 3 Before and After Weathering

Color Changes:

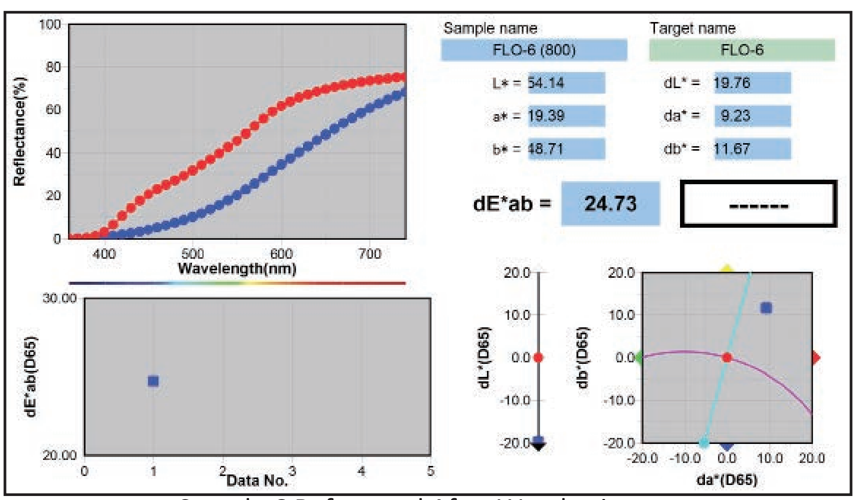
Flood CWF UV-5 Penetrating Wood Finish for Fences, Decks, and Siding (Natural Tone (Clear)):



Sample 4 Before and After Weathering



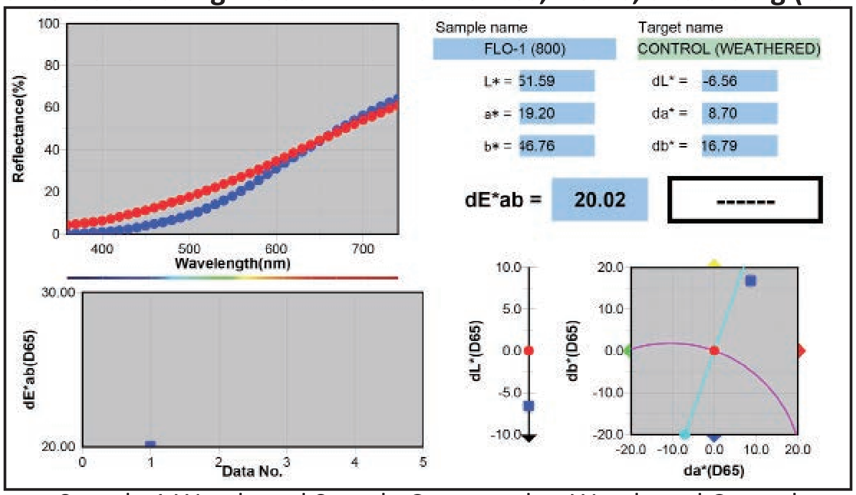
Sample 5 Before and After Weathering



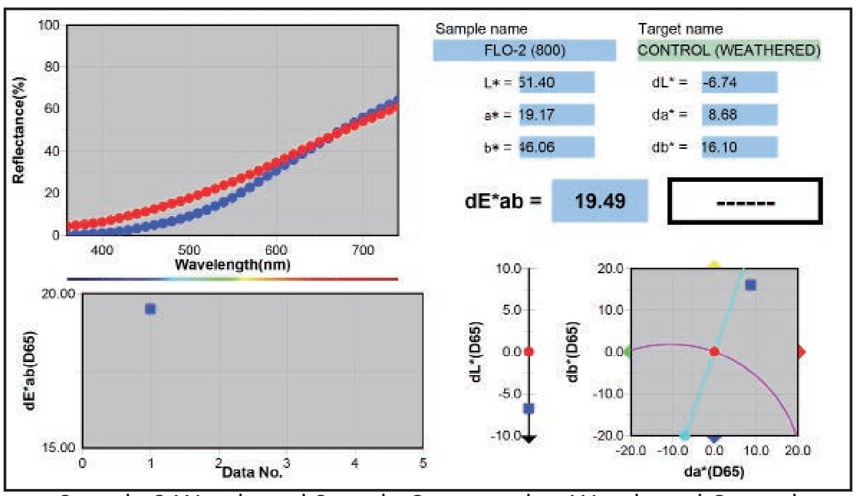
Sample 6 Before and After Weathering

Color Changes:

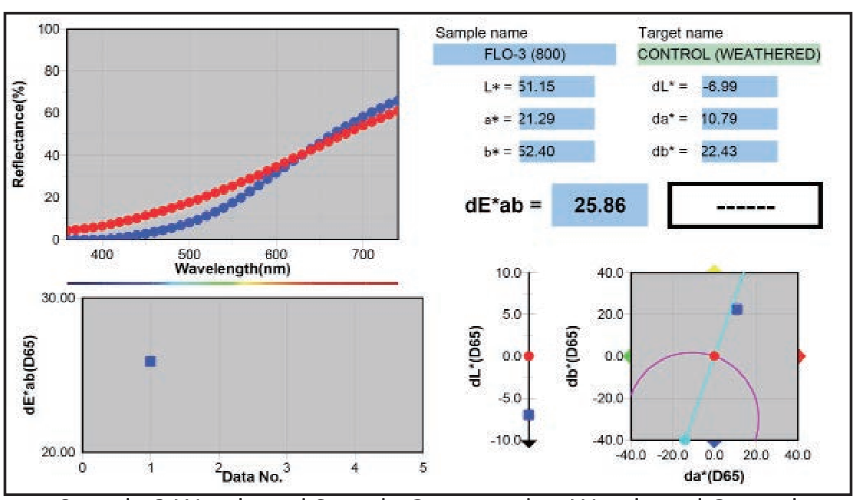
Flood CWF UV-5 Penetrating Wood Finish for Fences, Decks, and Siding (Natural Tone (Clear)):



Sample 1 Weathered Sample Compared to Weathered Control



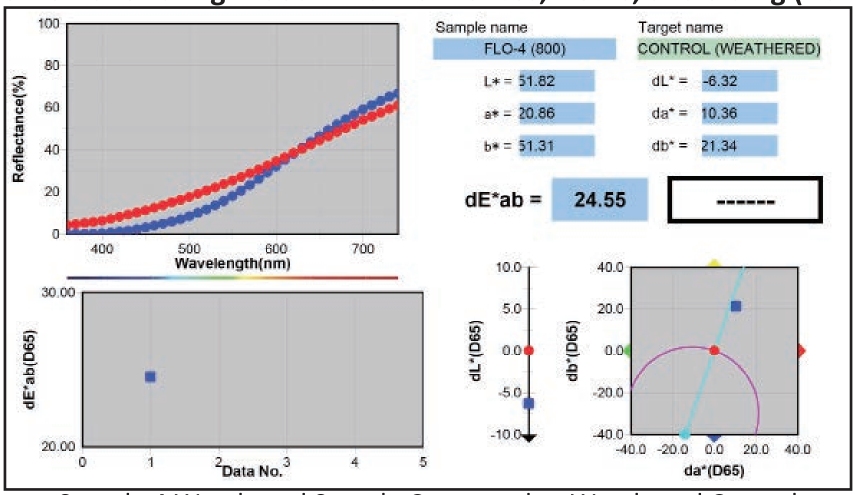
Sample 2 Weathered Sample Compared to Weathered Control



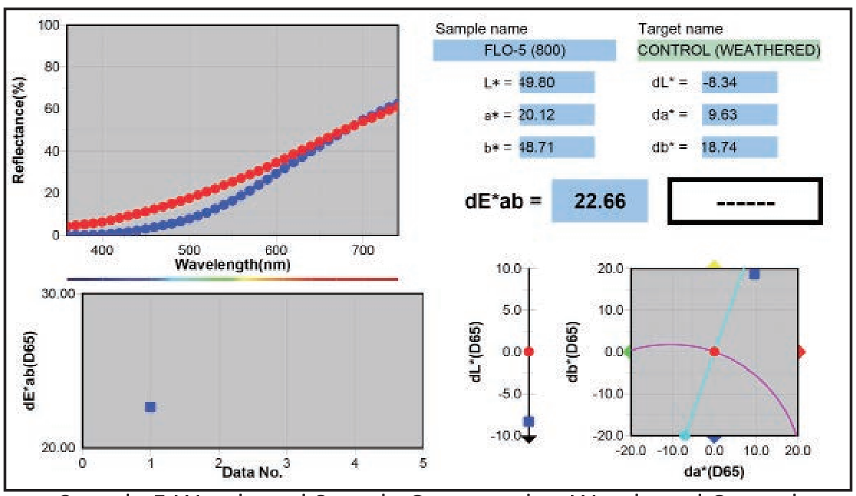
Sample 3 Weathered Sample Compared to Weathered Control

Color Changes:

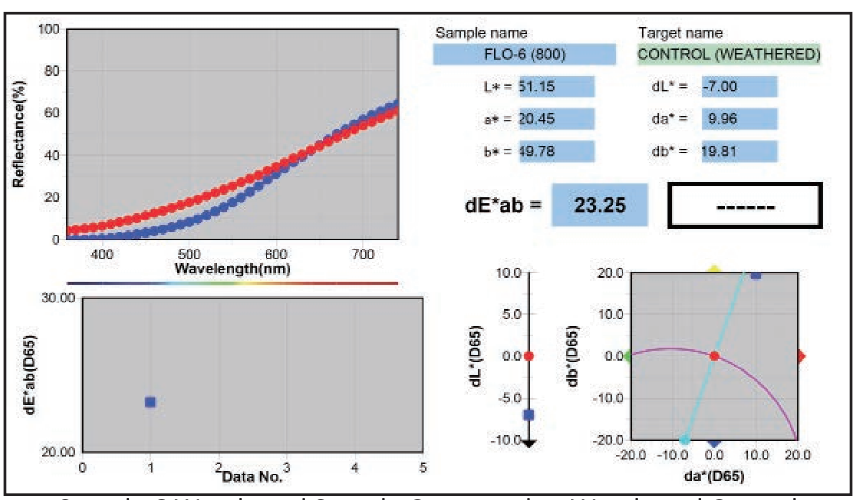
Flood CWF UV-5 Penetrating Wood Finish for Fences, Decks, and Siding (Natural Tone (Clear)):



Sample 4 Weathered Sample Compared to Weathered Control



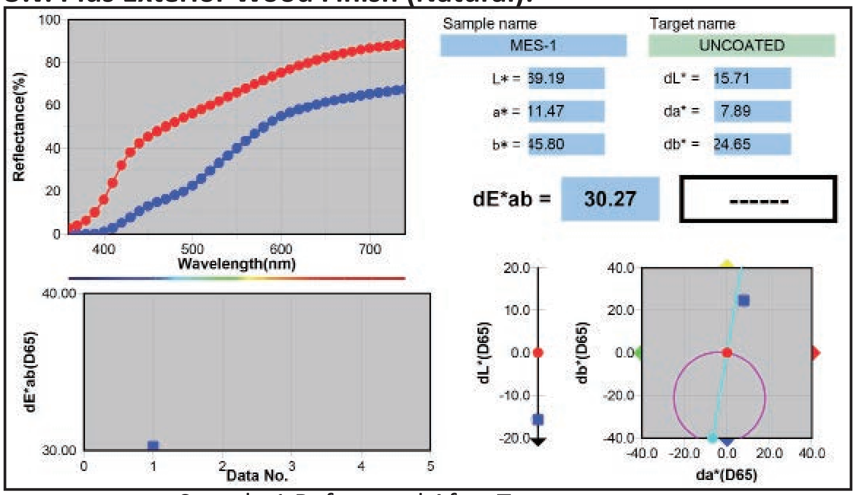
Sample 5 Weathered Sample Compared to Weathered Control



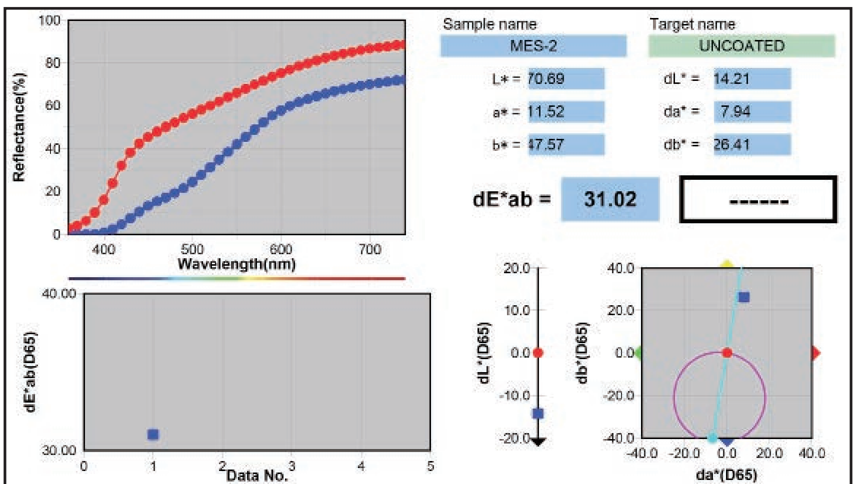
Sample 6 Weathered Sample Compared to Weathered Control

Color Changes:

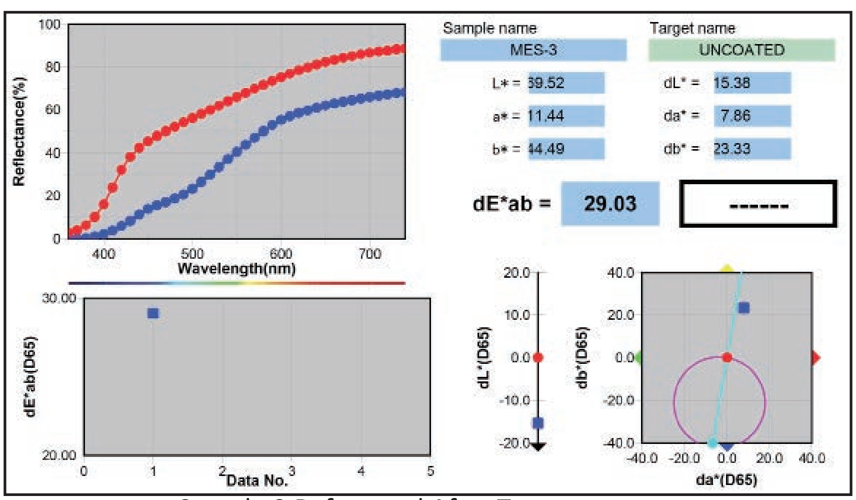
Messmer's U.V. Plus Exterior Wood Finish (Natural):



Sample 1 Before and After Treatment



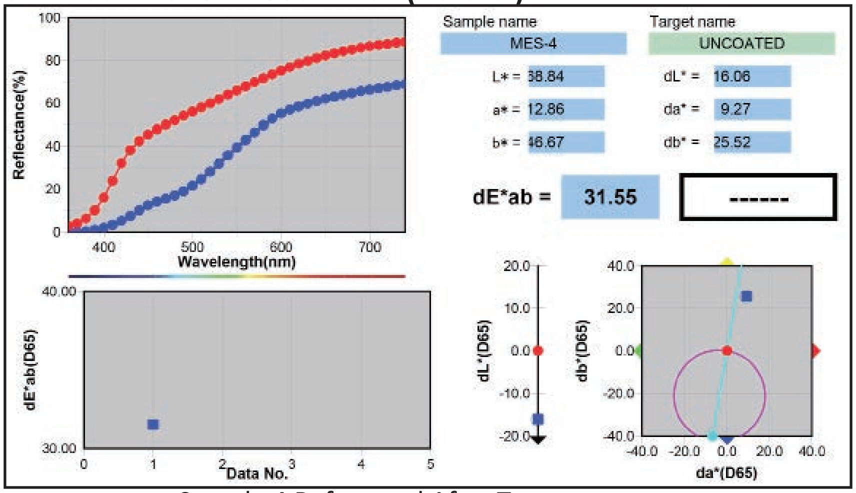
Sample 2 Before and After Treatment



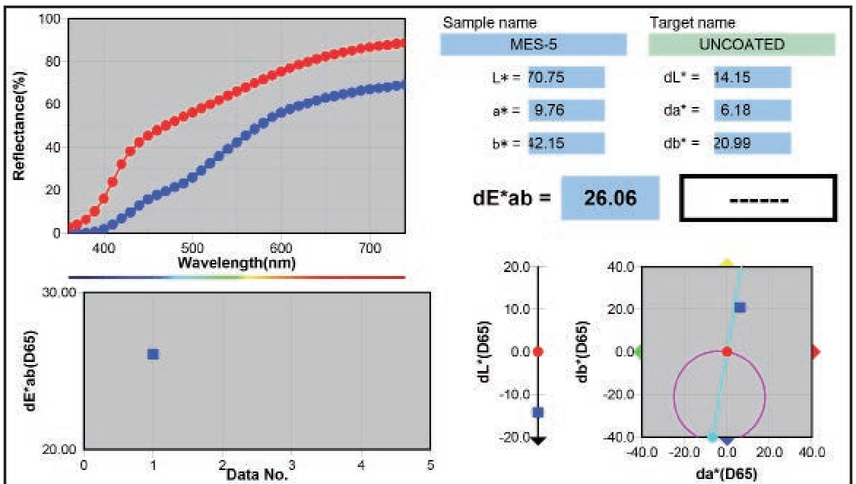
Sample 3 Before and After Treatment

Color Changes:

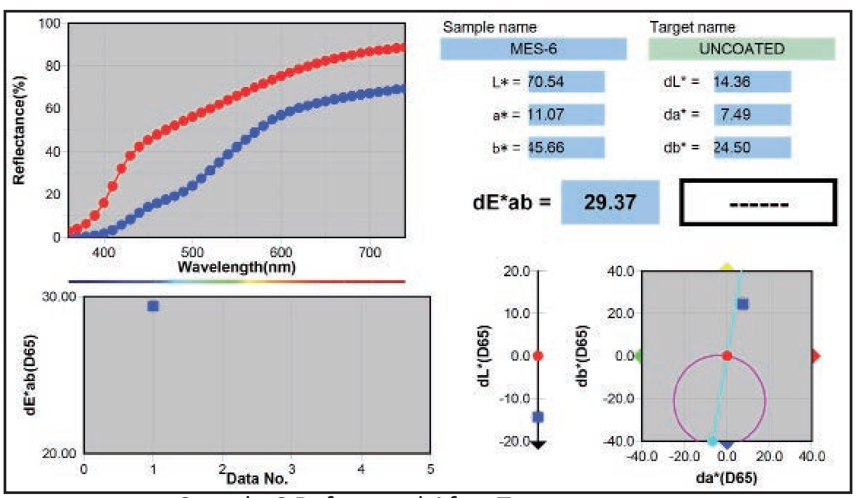
Messmer's U.V. Plus Exterior Wood Finish (Natural):



Sample 4 Before and After Treatment



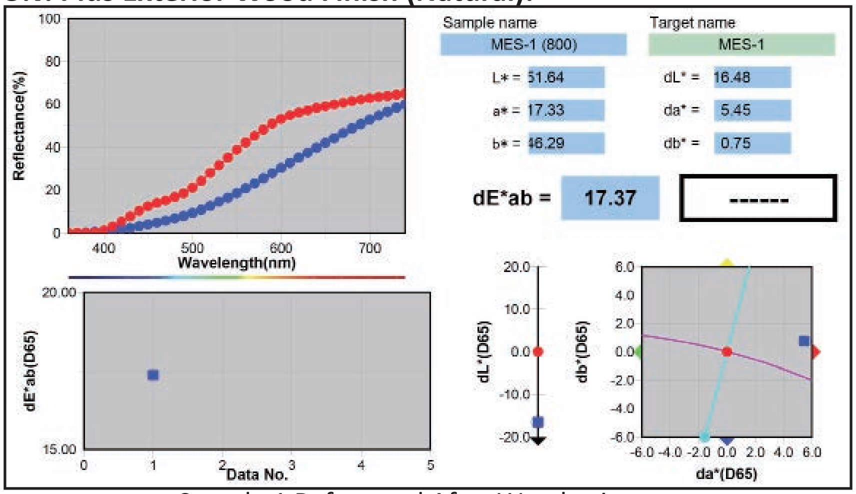
Sample 5 Before and After Treatment



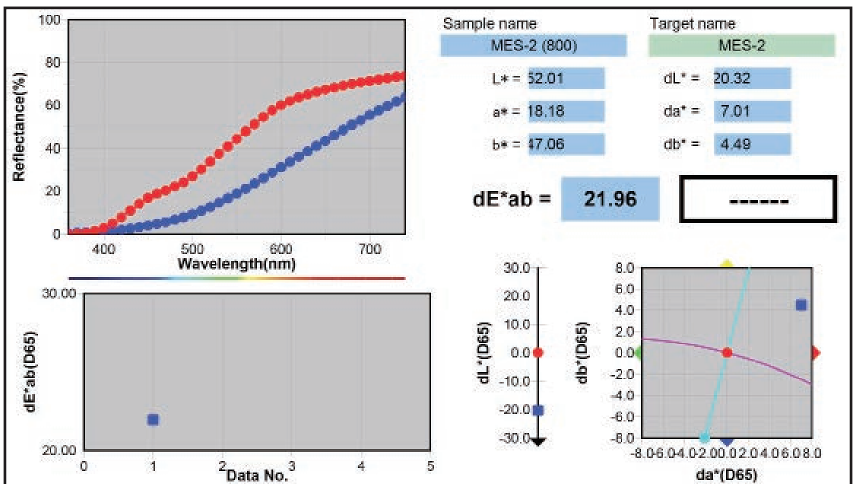
Sample 6 Before and After Treatment

Color Changes:

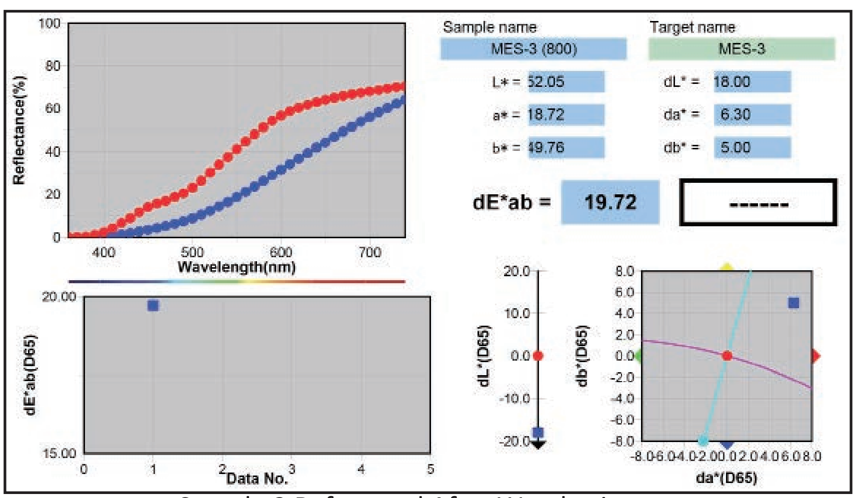
Messmer's U.V. Plus Exterior Wood Finish (Natural):



Sample 1 Before and After Weathering



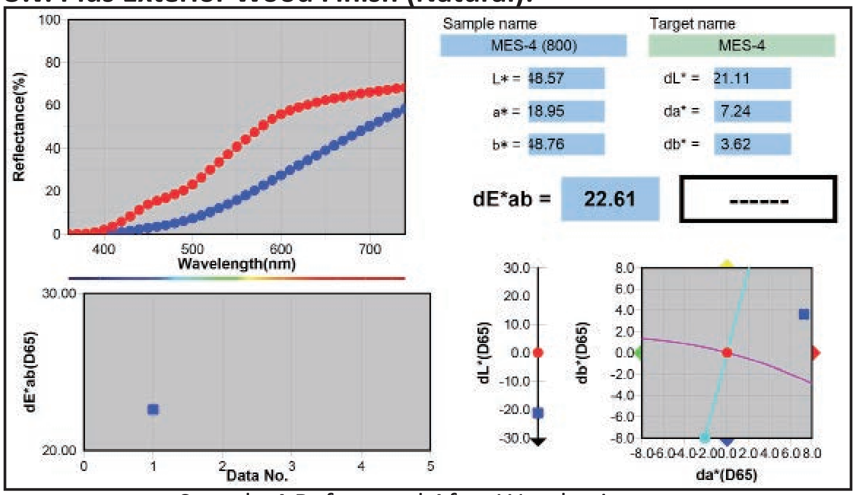
Sample 2 Before and After Weathering



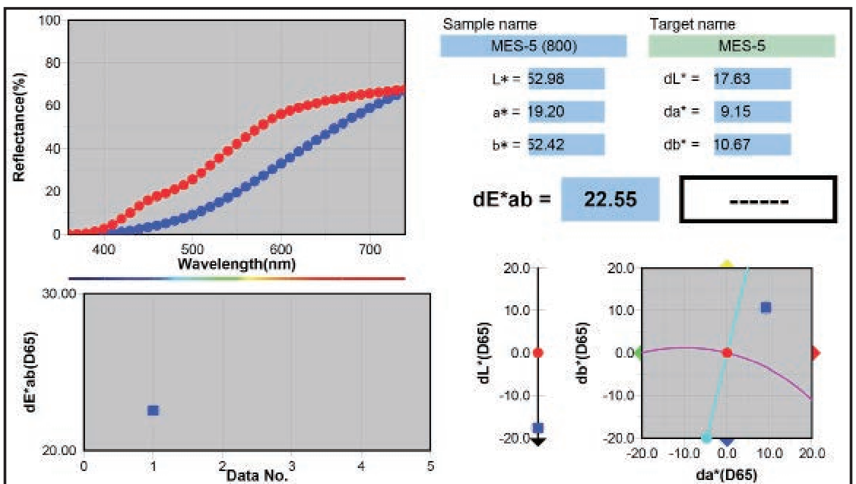
Sample 3 Before and After Weathering

Color Changes:

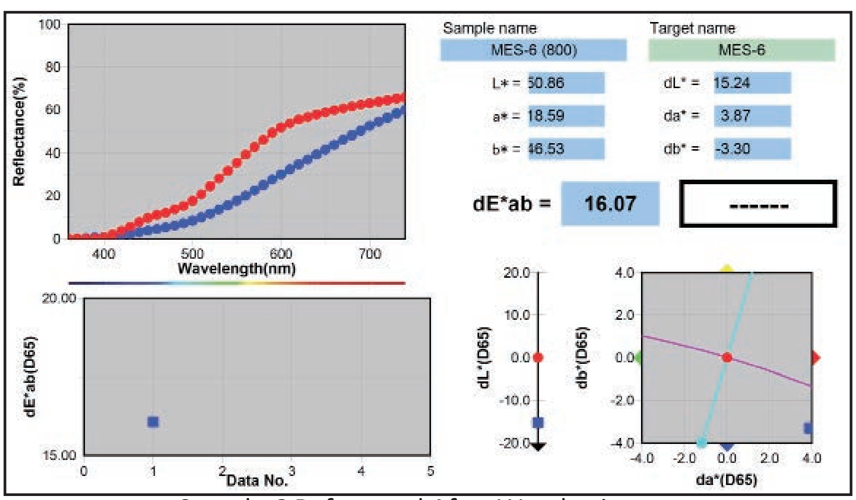
Messmer's U.V. Plus Exterior Wood Finish (Natural):



Sample 4 Before and After Weathering



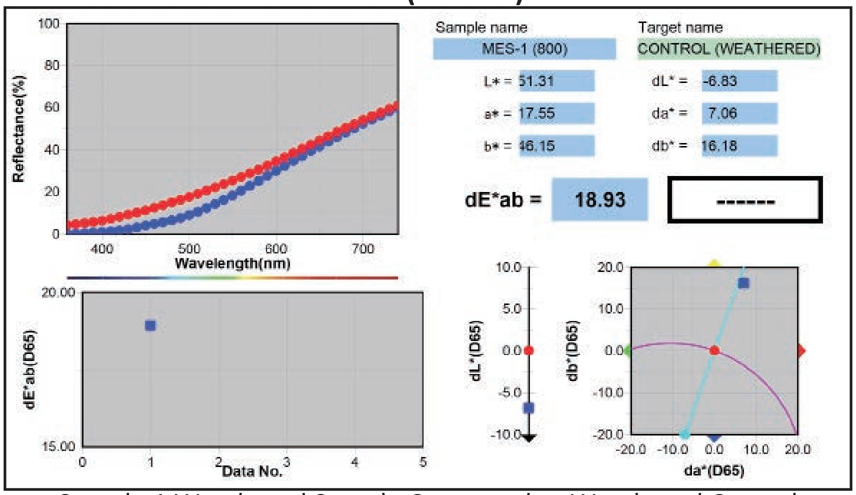
Sample 5 Before and After Weathering



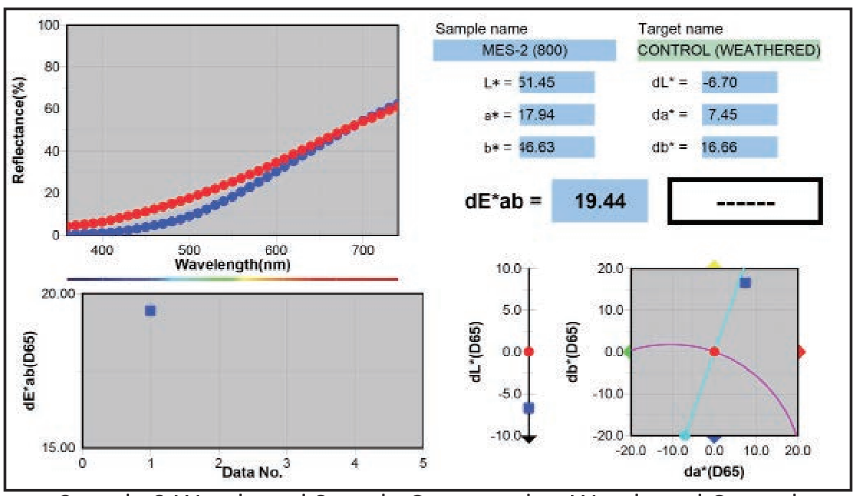
Sample 6 Before and After Weathering

Color Changes:

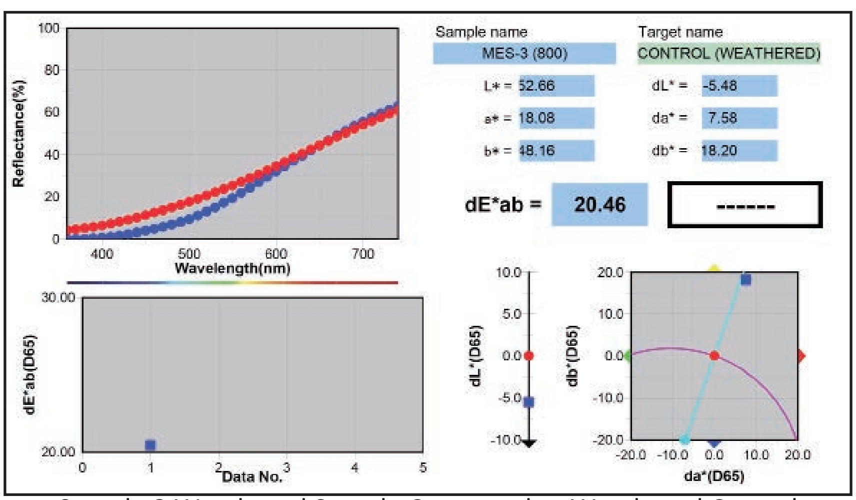
Messmer's U.V. Plus Exterior Wood Finish (Natural):



Sample 1 Weathered Sample Compared to Weathered Control



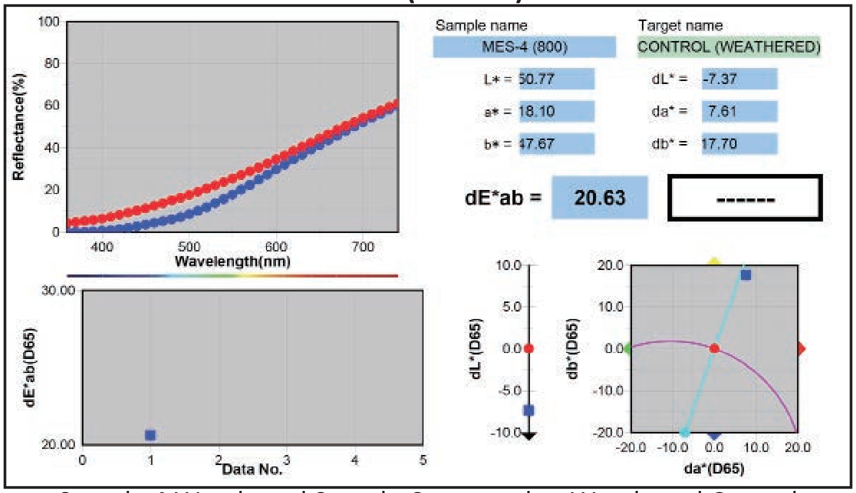
Sample 2 Weathered Sample Compared to Weathered Control



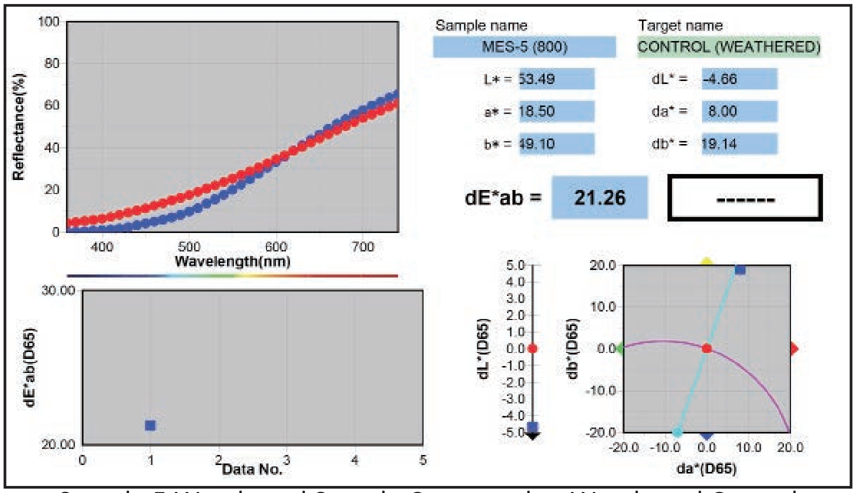
Sample 3 Weathered Sample Compared to Weathered Control

Color Changes:

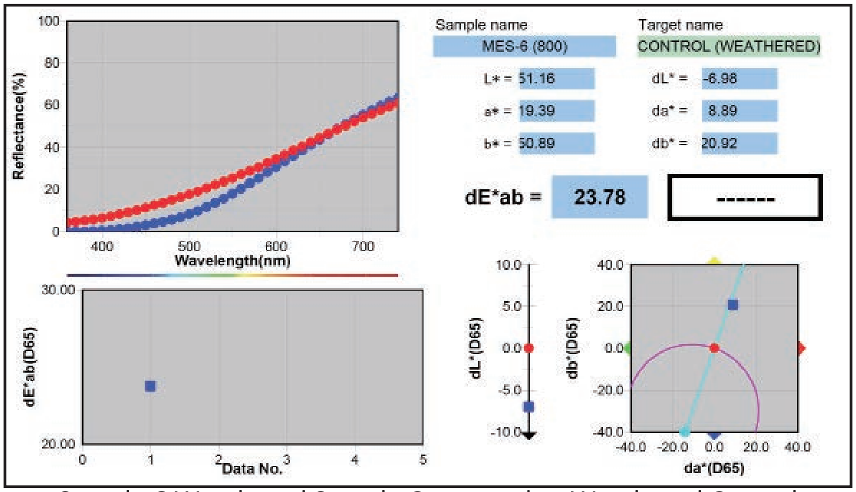
Messmer's U.V. Plus Exterior Wood Finish (Natural):



Sample 4 Weathered Sample Compared to Weathered Control



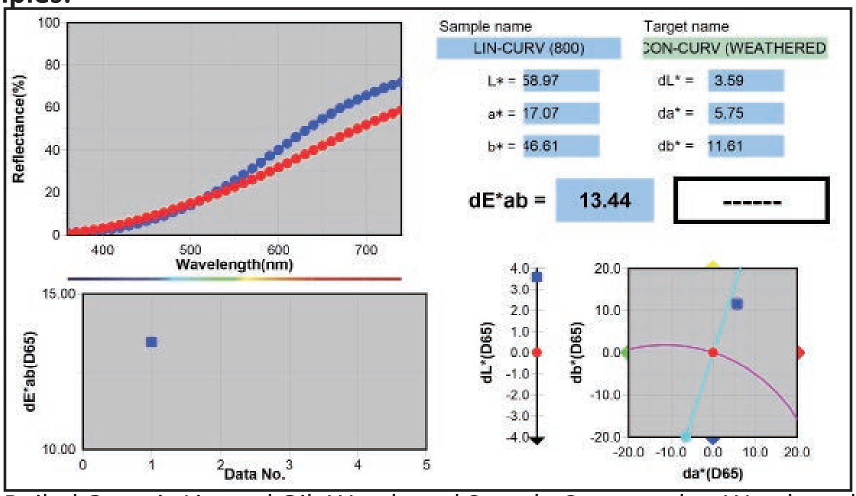
Sample 5 Weathered Sample Compared to Weathered Control



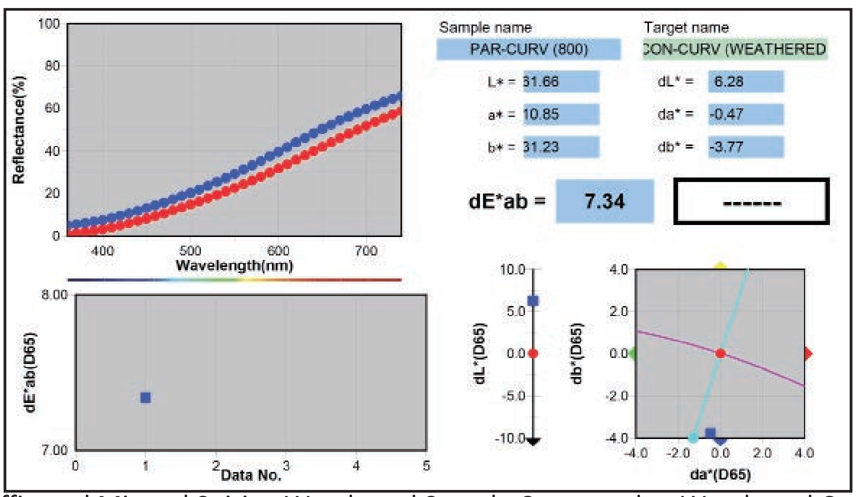
Sample 6 Weathered Sample Compared to Weathered Control

Color Changes:

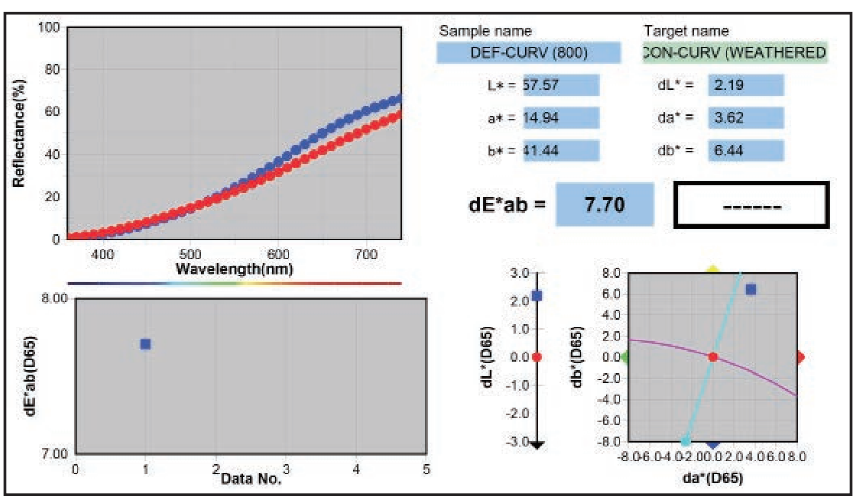
Curved Samples:



Allbäck Boiled Organic Linseed Oil: Weathered Sample Compared to Weathered Control

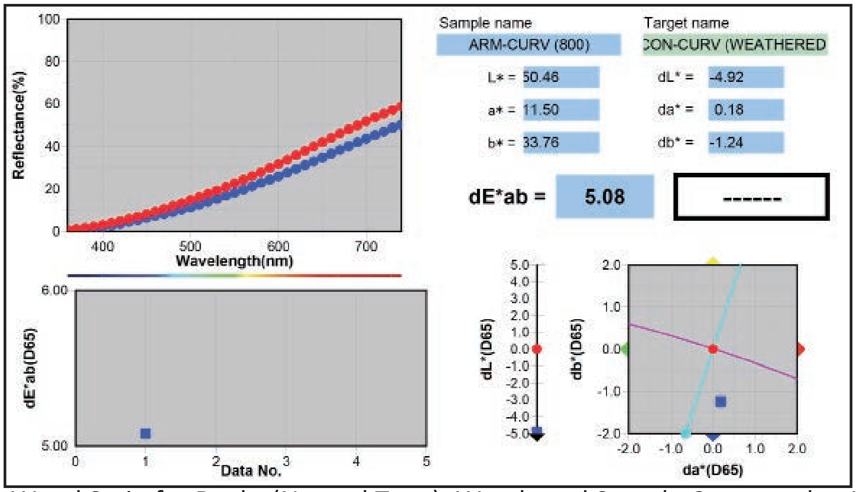


Paraffin and Mineral Spirits: Weathered Sample Compared to Weathered Control

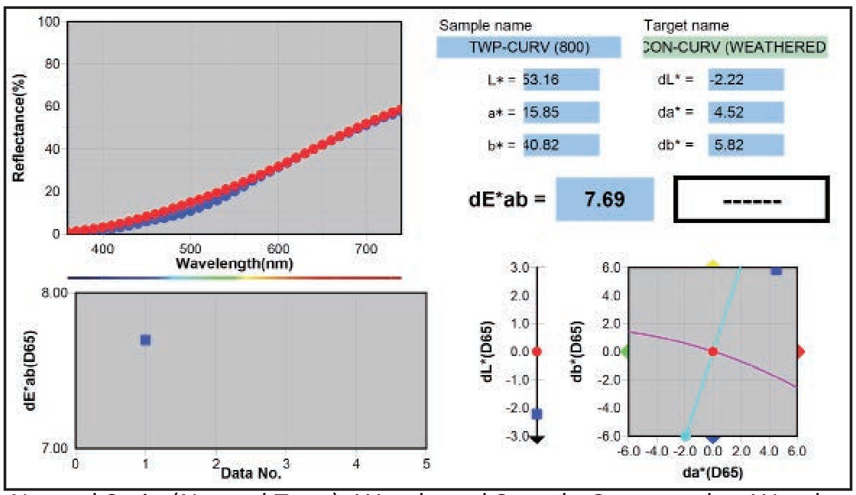


DEFY Extreme Exterior Clear Wood Stain: Weathered Sample Compared to Weathered Control

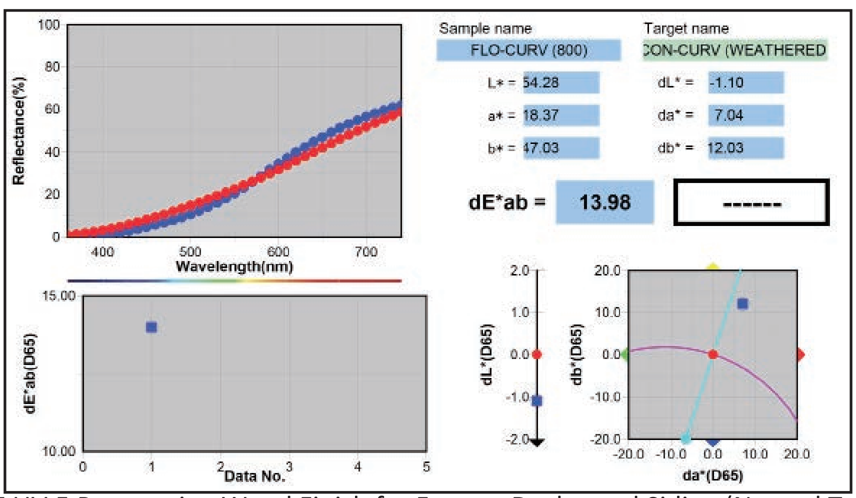
Color Changes:
Curved Samples:



Armstrong's Wood Stain for Decks (Natural Tone): Weathered Sample Compared to Weathered Control



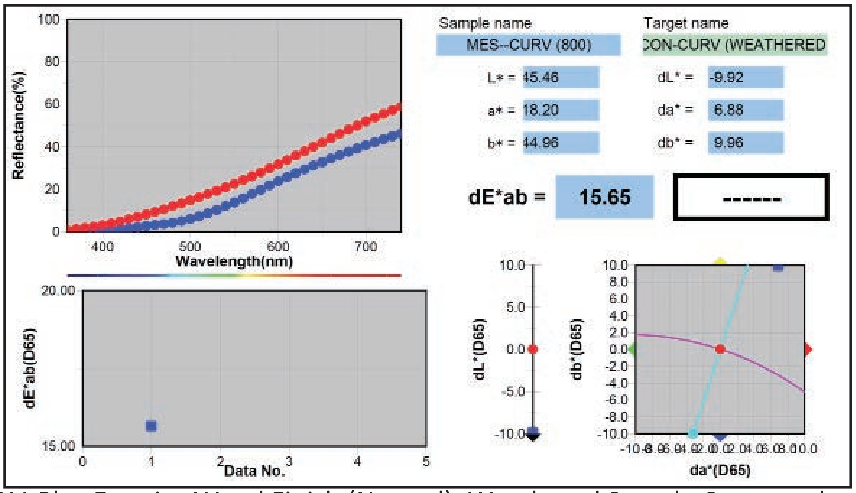
TWP 1500 Natural Stain (Natural Tone): Weathered Sample Compared to Weathered Control



Flood CWF UV-5 Penetrating Wood Finish for Fences, Decks, and Siding (Natural Tone (Clear)): Weathered Sample Compared to Weathered Control

Color Changes:

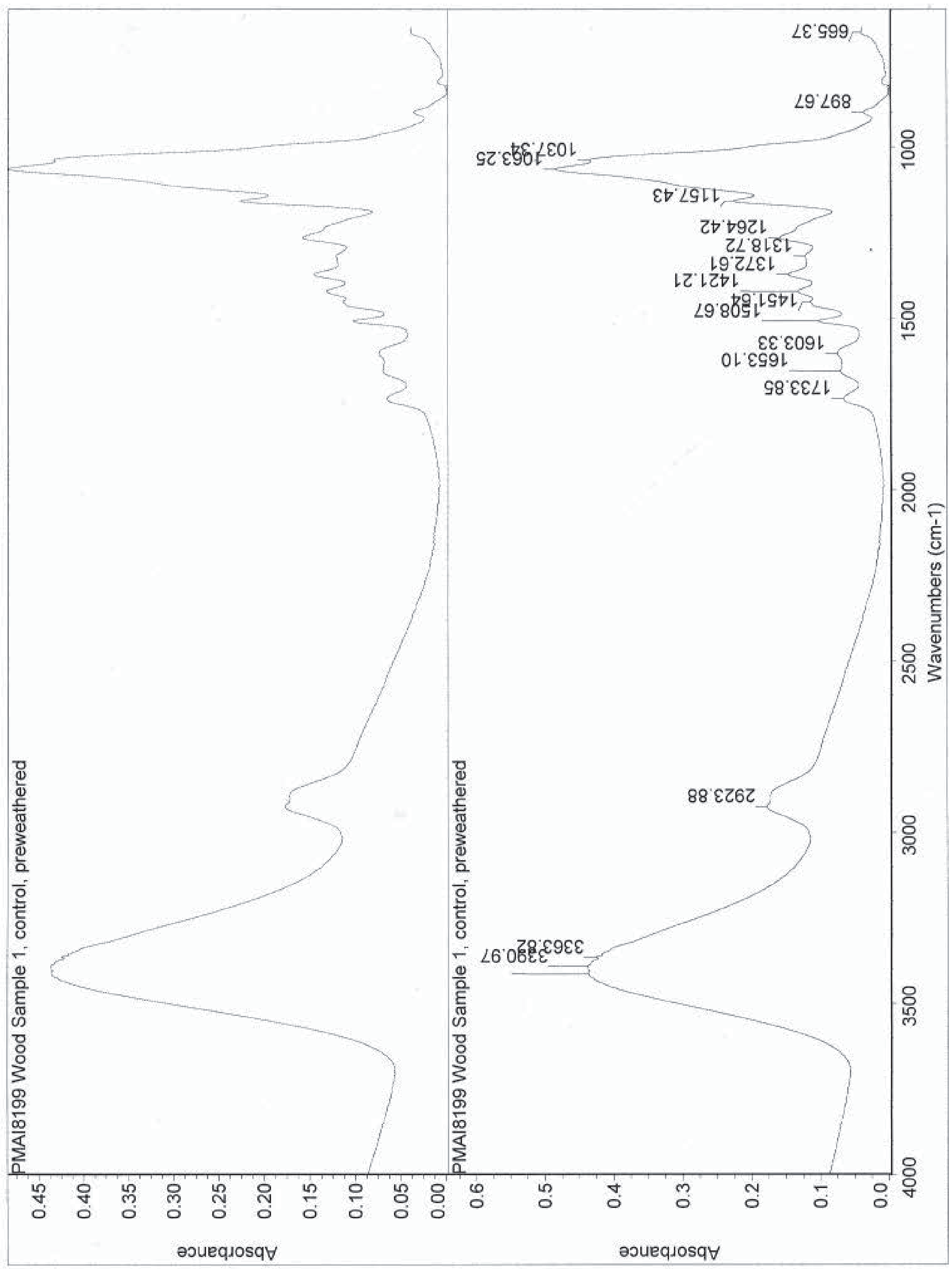
Curved Samples:



Messmer's U.V. Plus Exterior Wood Finish (Natural): Weathered Sample Compared to Weathered Control

Appendix D - Fourier Transform Infrared Spectroscopy (FTIR)

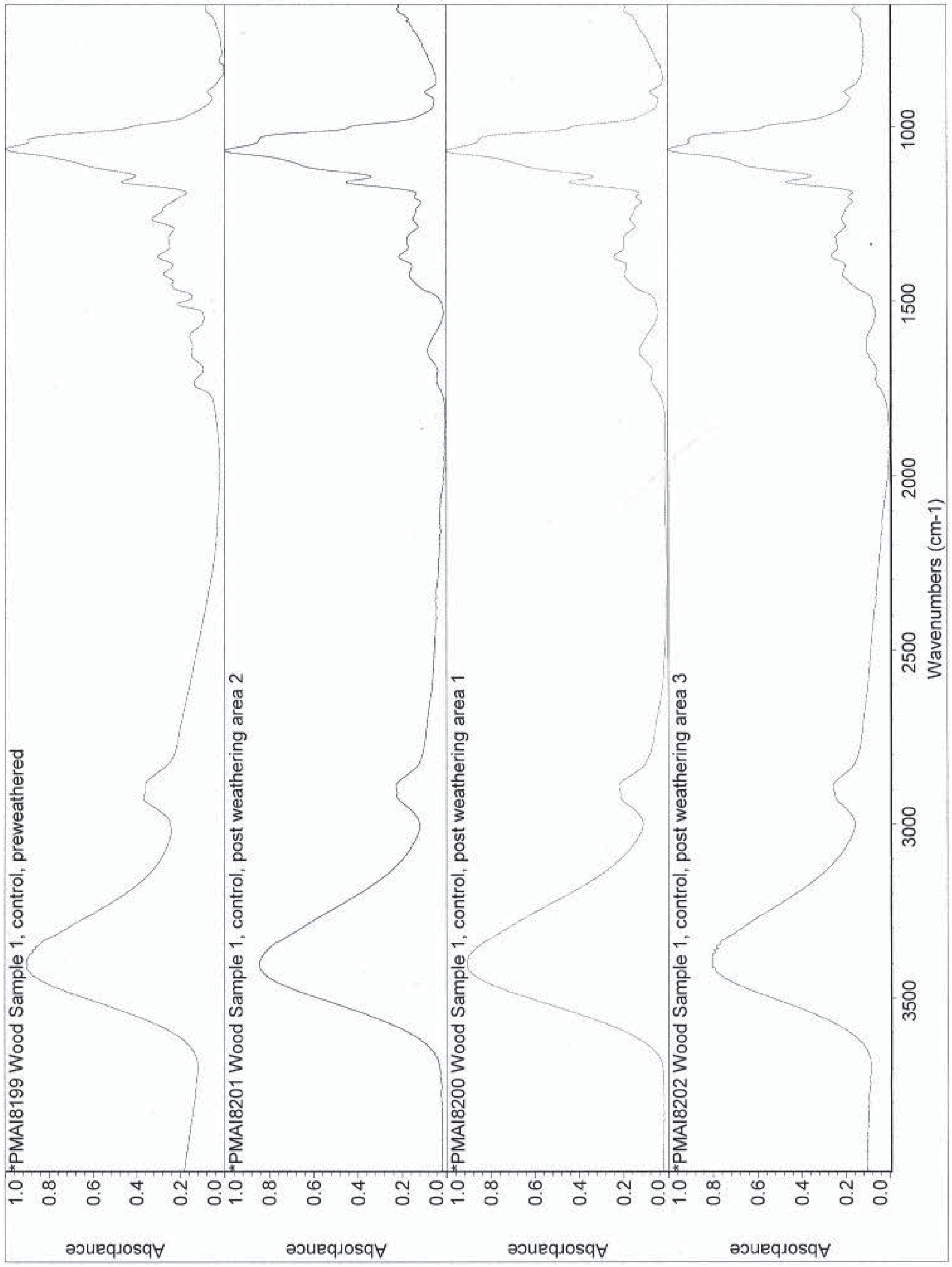
Control:



Unweathered sample of wood used to show the bands typical for a sample of relatively undamaged lodgepole pine. In particular, the peak at 1508 wavenumbers indicating the presence of lignin was useful in monitoring for degradation in the weathering process.

Fourier Transform Infrared Spectroscopy (FTIR):

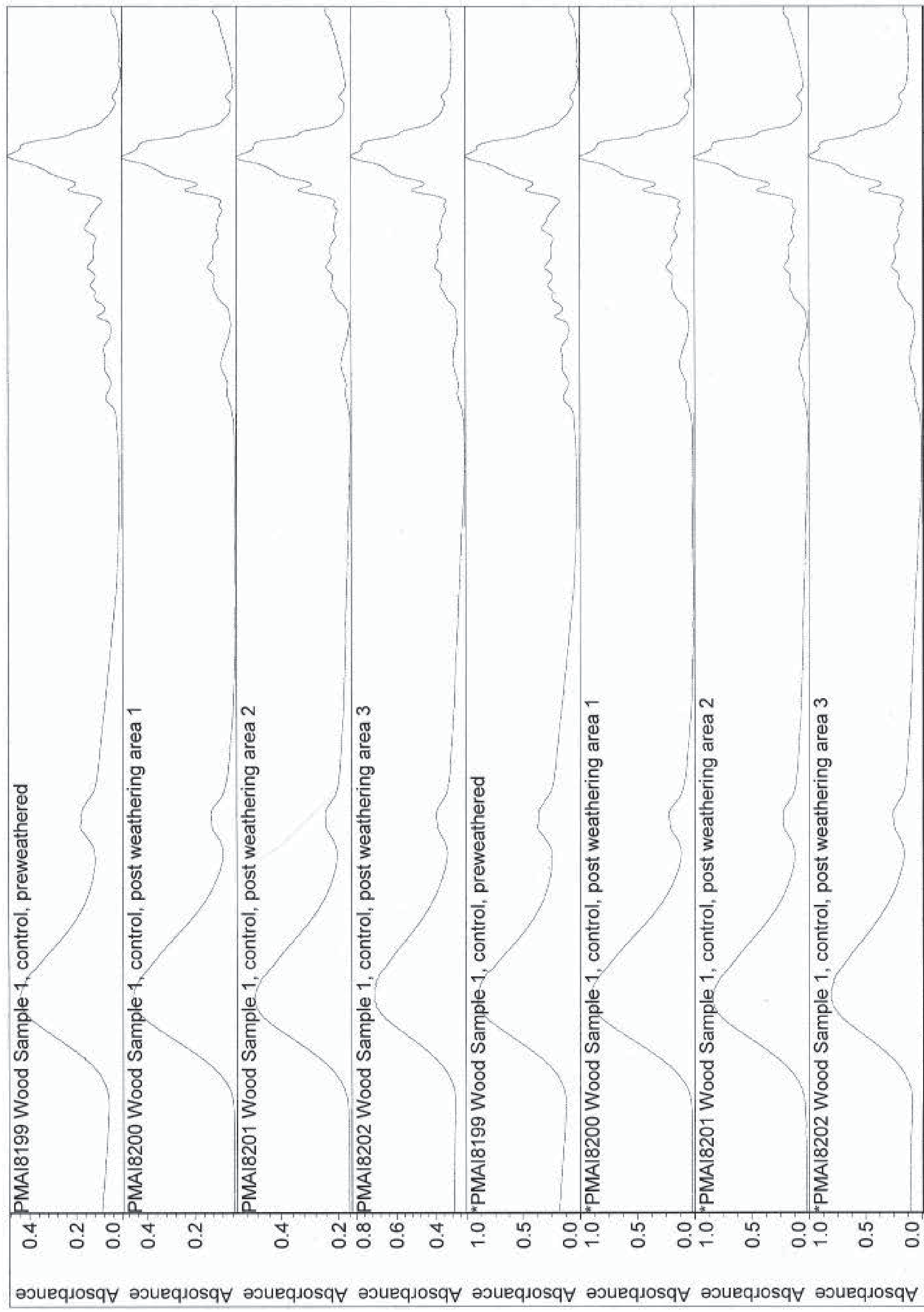
Control:



Sample of Control 1 before and after weathering. The weathered control was sampled in three locations to confirm results. The noticeable absence of the peak at 1508 that represents lignin confirmed the choice to use the peak or lack thereof as a tag for degradation.

Fourier Transform Infrared Spectroscopy (FTIR):

Control:



More tests on pre- and post-weathered samples of control sample 1 to confirm the bands and intensities of lodgepole pine before and after UV degradation.

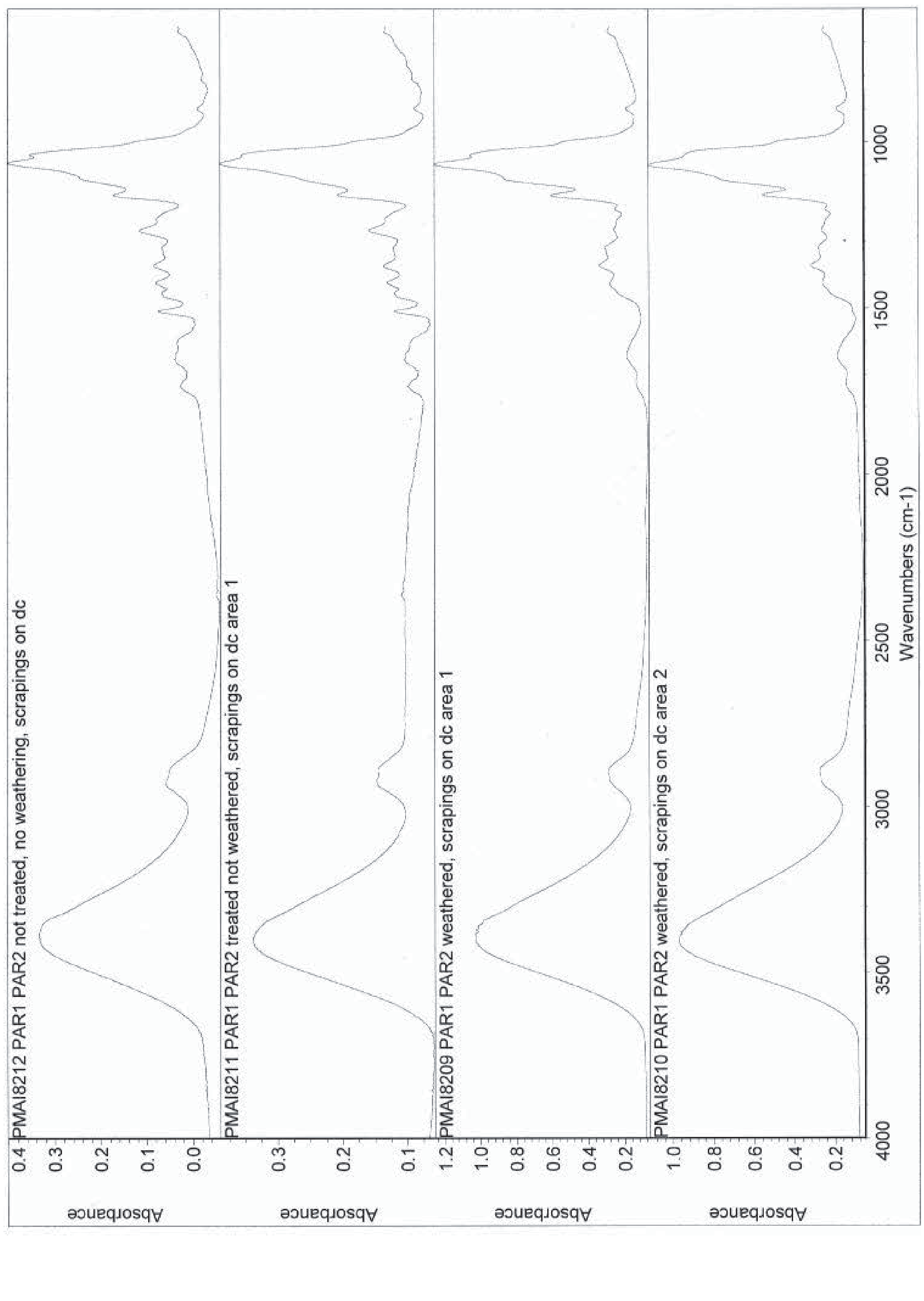
Fourier Transform Infrared Spectroscopy (FTIR):

Allbäck Boiled Organic Linseed Oil:

Spectra for sample 1 of the linseed oil cohort showing (from the top down) wood pre-treatment, wood treated with linseed oil but not weathered, treated wood that has been weathered from two areas, and standards of comparison for linseed oil's spectrum. Lack of 1508 lignin peak in the weathered samples.

Fourier Transform Infrared Spectroscopy (FTIR):

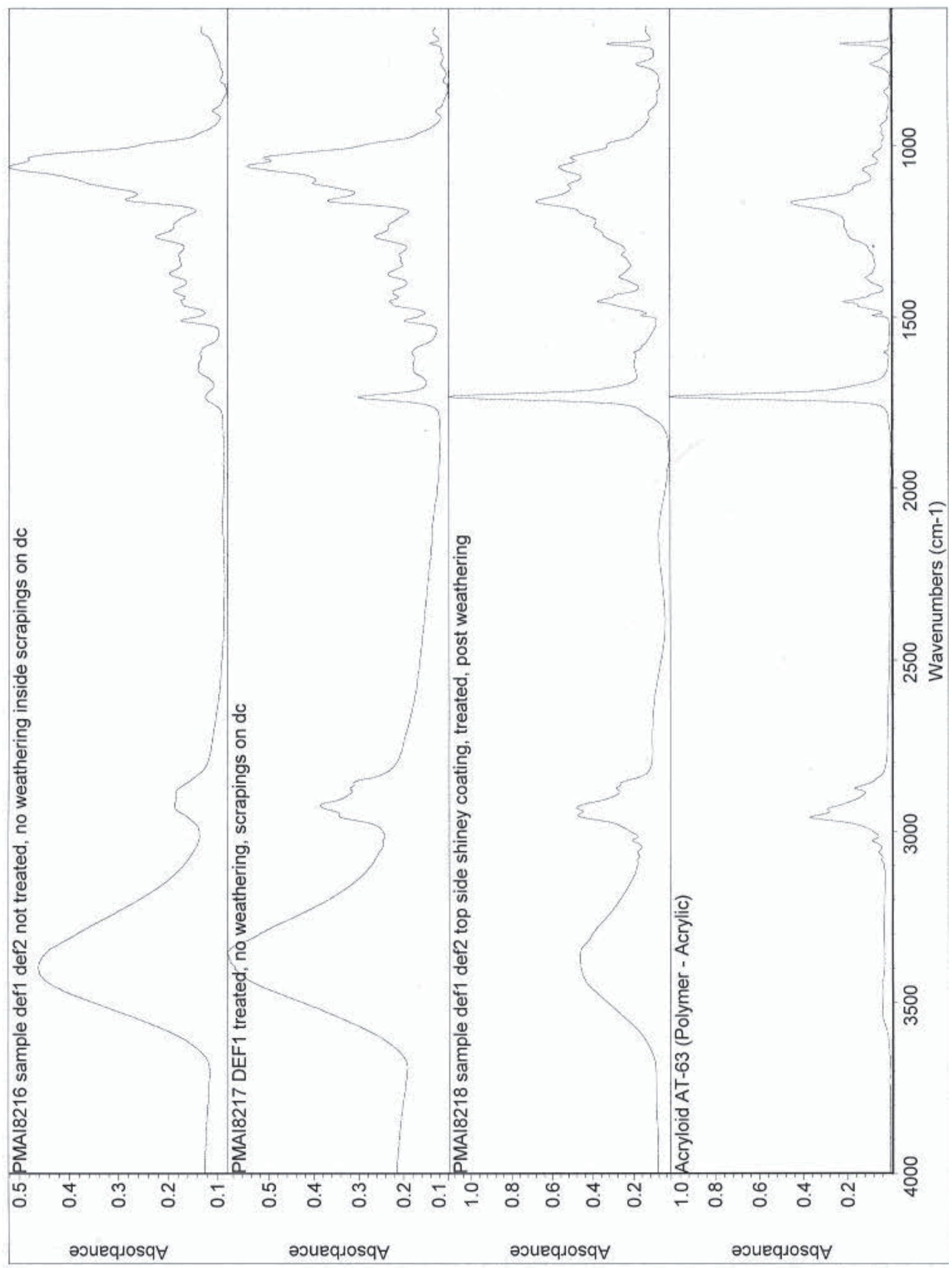
Paraffin and Mineral Spirits:



Spectra for sample 1 of the paraffin and mineral spirits cohort showing (from the top down) wood pre-treatment, wood treated with paraffin and mineral spirits but not weathered, and treated wood that has been weathered from two areas. The 1508 lignin peak in the weathered samples is minimal at best.

Fourier Transform Infrared Spectroscopy (FTIR):

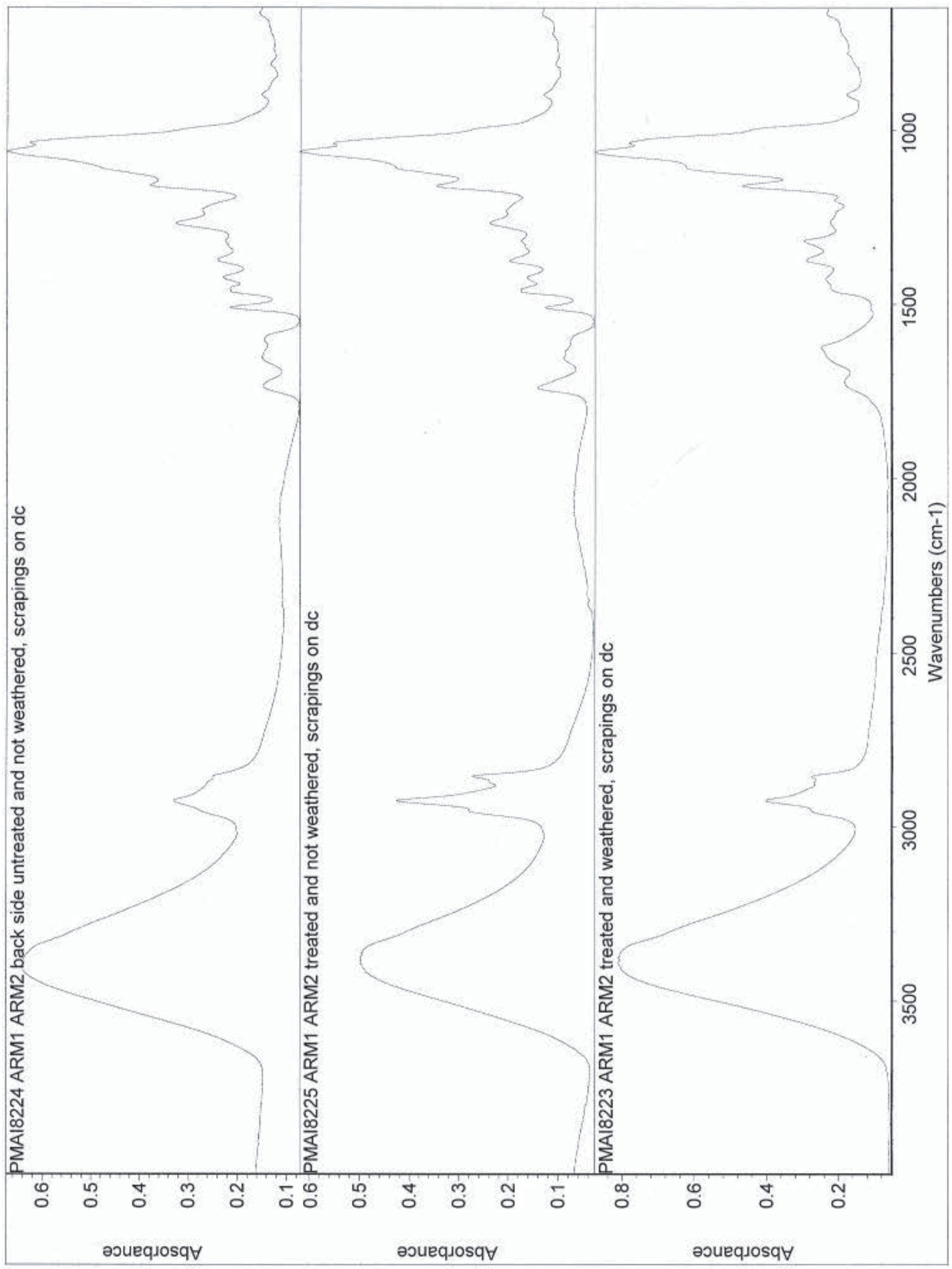
DEFY Extreme Exterior Clear Wood Stain:



Spectra for sample 1 of the DEFY Extreme cohort showing (from the top down) wood pre-treatment, wood treated with DEFY but not weathered, treated wood that has been weathered, and standards of comparison for an acrylic polymer for comparison with the DEFY product. Very small intensity for 1508 lignin peak in the weathered sample indicates there might be lignin remaining.

Fourier Transform Infrared Spectroscopy (FTIR):

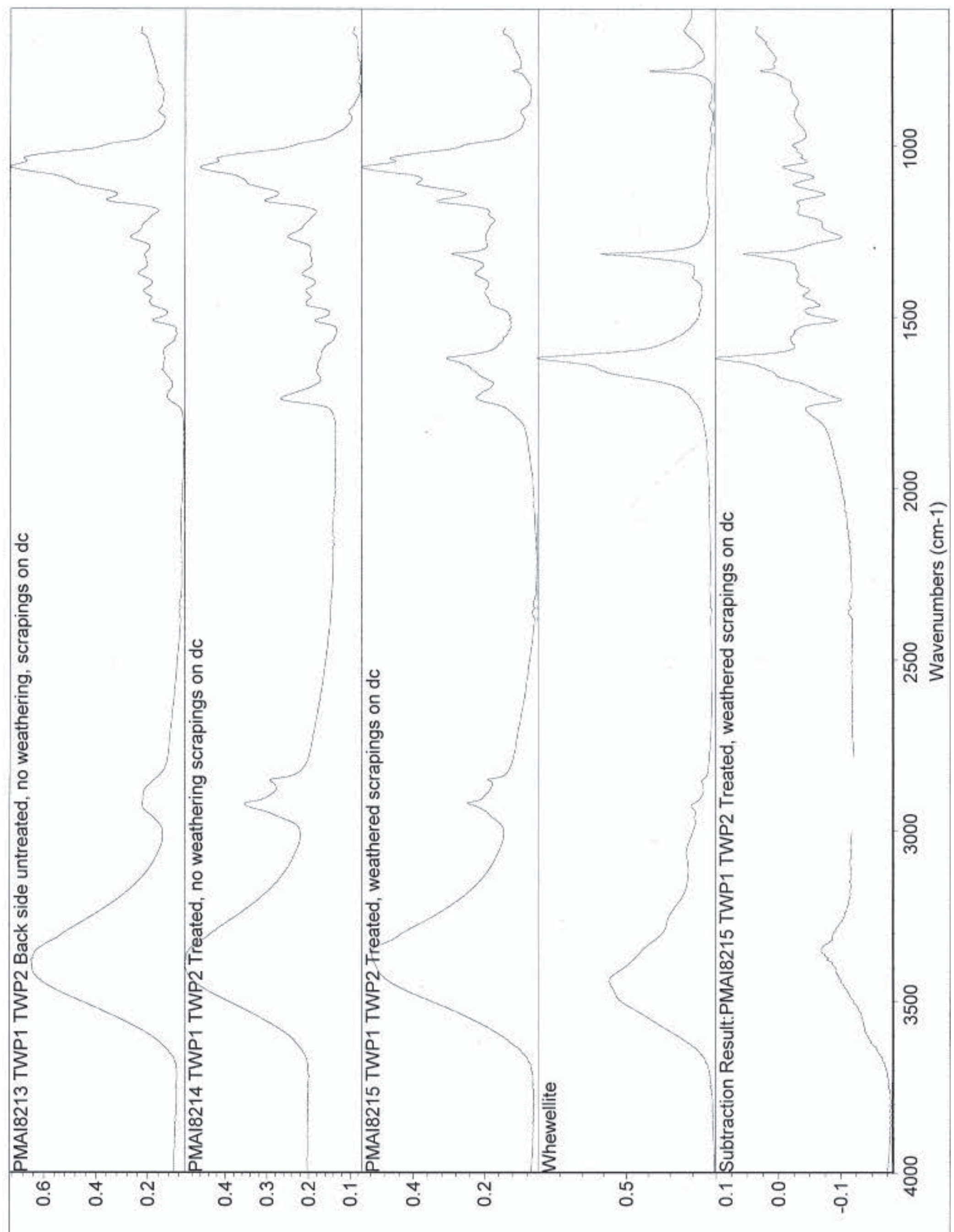
Armstrong's Wood Stain for Decks (Natural Tone):



Spectra for sample 1 of the Armstrong's Wood Stain cohort showing (from the top down) wood pre-treatment, wood treated with Armstrong but not weathered, and treated wood that has been weathered. Very small intensity for 1508 lignin peak in the weathered sample indicates there might be some lignin remaining, but most is gone.

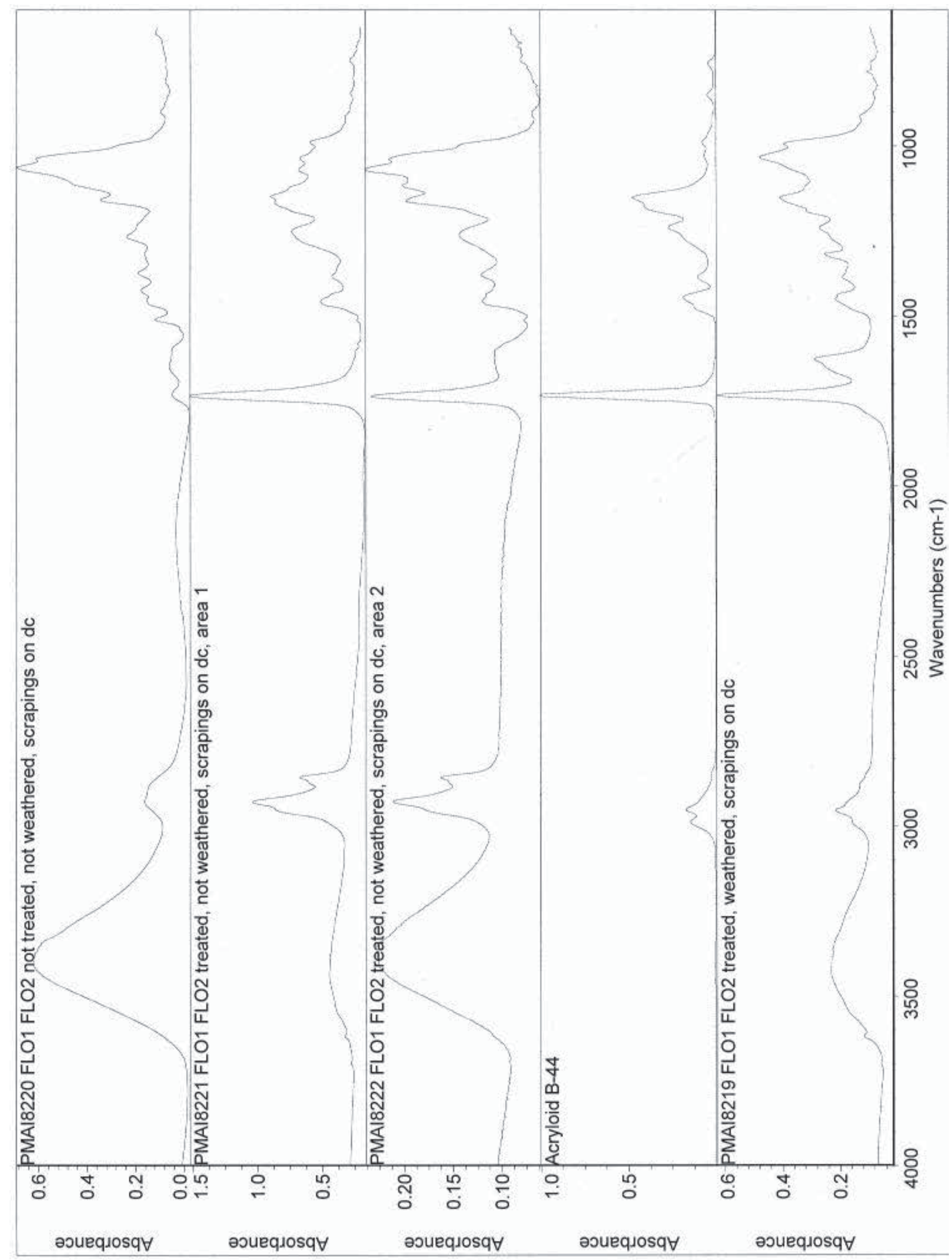
Fourier Transform Infrared Spectroscopy (FTIR):

TWP 1500 Natural Stain (Natural Tone):



Spectra for sample 1 of the TWP 1500 cohort showing (from the top down) wood pre-treatment, wood treated with TWP but not weathered, treated wood that has been weathered, and spectra for whewellite (a calcium oxalate coating likely derived from a calcium drier) with a subtraction spectrum of TWP in an attempt to identify some components of the treatment. The 1508 lignin peak in the weathered sample appears to entirely gone.

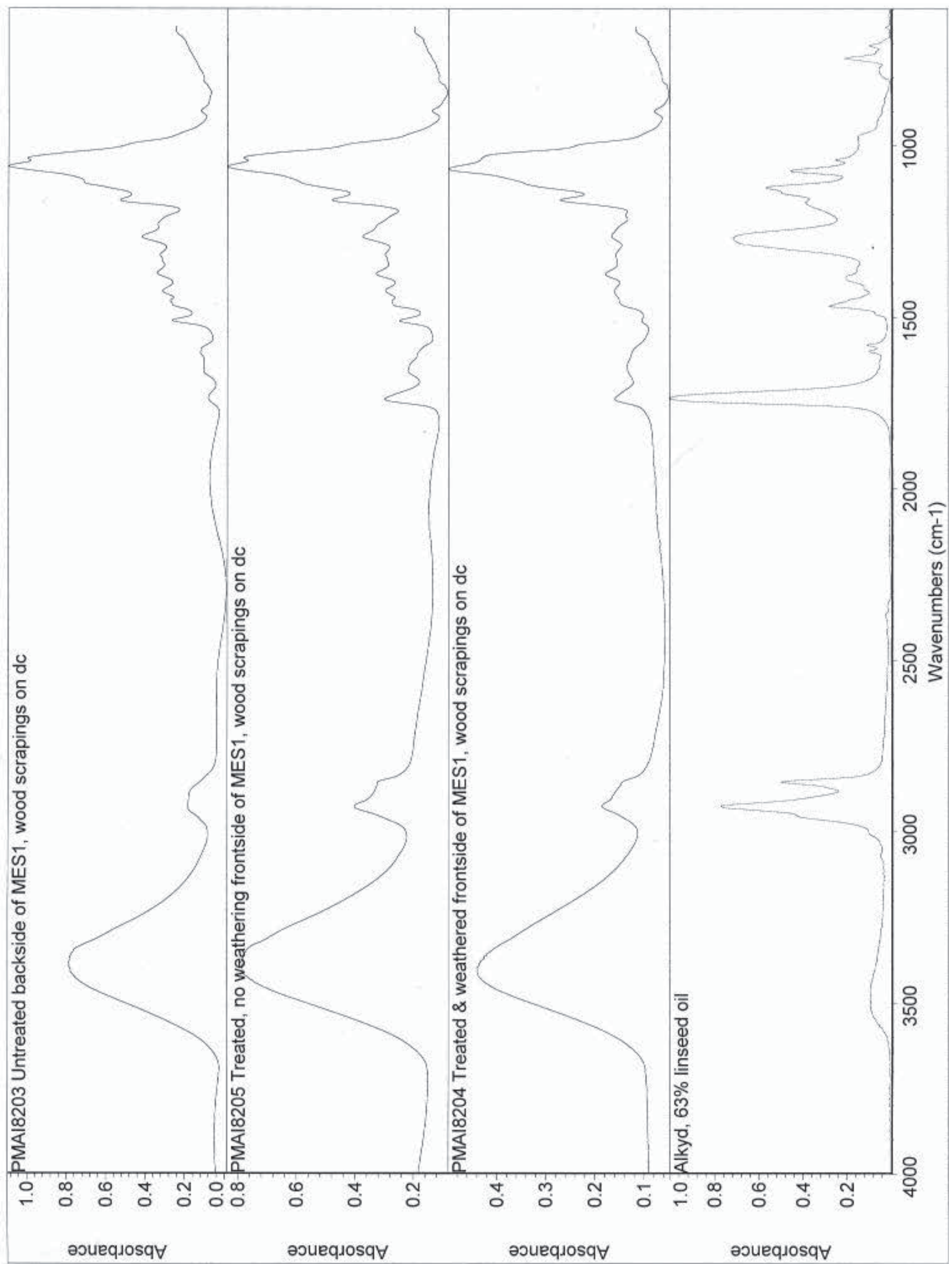
Fourier Transform Infrared Spectroscopy (FTIR):
Flood CWF UV-5 Penetrating Wood Finish for Fences, Decks, and Siding (Natural Tone (Clear)):



Spectra for sample 1 of the Flood CWF UV-5 cohort showing (from the top down) wood pre-treatment, wood treated with Flood but not weathered from two different areas, an acryloid that may shed light on Flood's composition, and treated wood that has been weathered. There may have been interference with the 1508 lignin peak from the Flood product, but the weathered sample appears to not have a peak at 1508.

Fourier Transform Infrared Spectroscopy (FTIR):

Messmer's U.V. Plus Exterior Wood Finish (Natural):



Spectra for sample 1 of the Messmer's UV Plus cohort showing (from the top down) wood pre-treatment, wood treated with Messmer's but not weathered, treated wood that has been weathered, and a spectrum for linseed oil for comparison to Messmer's composition. There is a small peak at 1508 remaining indicating that some lignin still remains in the surface sample.

Appendix E - Water Repellency

Summary of Found Contact Angles:

	Sample	Pre-Weathering Left Angle (˚)	Pre-Weathering Right Angle (˚)	Post-Weathering Left Angle (˚)	Post-Weathering Right Angle (˚)
Control					
	CON-1	97.9	87.6	135.9	132.1
	CON-2	95.9	88.4	127.5	134.7
	CON-3	94.5	90.4	149	140.2
	CON-4	107.4	104.8	141.9	151.1
	CON-5	80.3	80.3	109.3	67.9
	CON-6	96.2	91.1	100.7	96.8
Linseed Oil					
	LIN-1	84.9	84.9	85	82.1
	LIN-2	81.3	78.9	71.6	78.5
	LIN-3	85.6	86.7	83.5	85.2
	LIN-4	77.7	73.8	66.9	65.9
	LIN-5	71.9	68.7	72.4	72.1
	LIN-6	86.4	81.9	70.1	78.7
Paraffin and Mineral Spirits					
	PAR-1	77.9	80.4	n/a	n/a
	PAR-2	74.4	74.2	n/a	n/a
	PAR-3	93.9	88	n/a	n/a
	PAR-4	67.7	64.7	146.7	70.7
	PAR-5	84.8	88.7	76.9	113
	PAR-6	75.2	76.9	131.4	132.5
DEFY Extreme (Clear)					
	DEF-1	107.8	99.9	86.2	82.1
	DEF-2	93.1	97.6	79.9	80.5
	DEF-3	74.9	72.8	76.8	78.4
	DEF-4	57	58.8	81.2	86.6
	DEF-5	64.2	61.8	88.4	86.4
	DEF-6	61.4	61.2	77.7	81.3
Armstrong (Natural)					
	ARM-1	63	66.4	76.6	73.6
	ARM-2	67.6	65.6	82.2	88.3
	ARM-3	74.2	72	68.6	69.5
	ARM-4	64.7	64.5	69.3	69.5
	ARM-5	75.7	74.8	84.2	79.6
	ARM-6	67.8	69.9	78.9	74.8
TWP 1500 (Natural)					
	TWP-1	67.4	69	71.2	73.3
	TWP-2	59.9	59.1	57.8	56.6
	TWP-3	68.6	69.2	60.1	63.1
	TWP-4	47.7	49.1	61.4	67.5

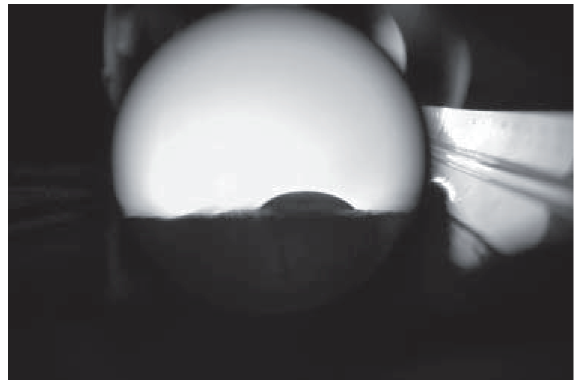
Summary of Found Contact Angles:

	TWP-5	67.4	69.5	67.1	72.2
	TWP-6	65.5	65.5	65.1	65.6
Flood CWF UV-5 (Natural)					
	FLO-1	74.2	74.4	92.4	109.9
	FLO-2	79.7	80.6	101.3	100.5
	FLO-3	78.9	77.5	106.4	107.5
	FLO-4	96.4	96.5	94.4	97.2
	FLO-5	83.1	84.1	94.9	95.8
	FLO-6	80.2	88.2	98.3	97.1
Messmer's UV Plus (Natural)					
	MES-1	81.8	80.3	71.5	69.8
	MES-2	80.3	77.9	80.2	88.8
	MES-3	76.2	77.4	78.5	80.3
	MES-4	92.5	88.4	72.3	73.6
	MES-5	72.8	71.2	62	60.8
	MES-6	68.8	69.4	70.2	70.7

Testing Images for Contact Angles:

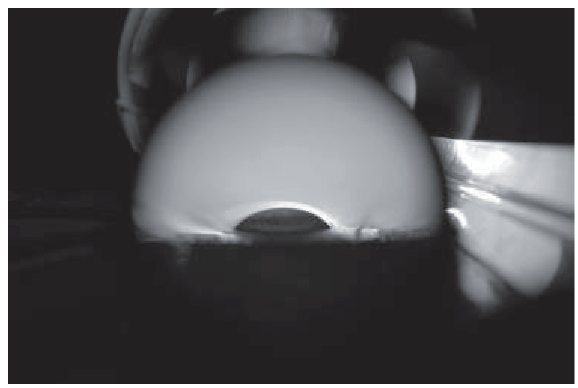
Control:

Control 1, Pre-Weathering

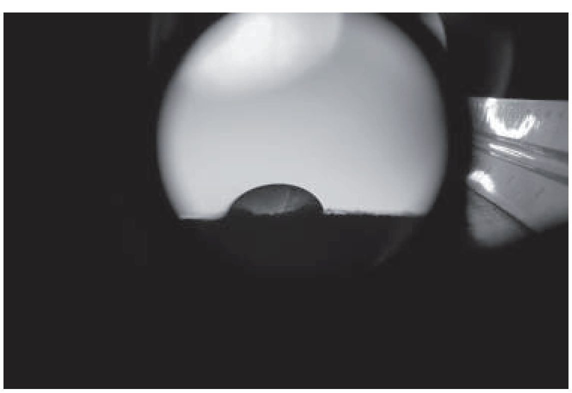


Control 1, Post-Weathering

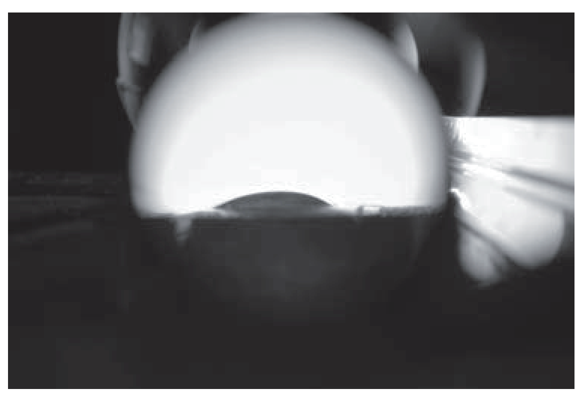
Control 2, Pre-Weathering



Control 2, Post-Weathering



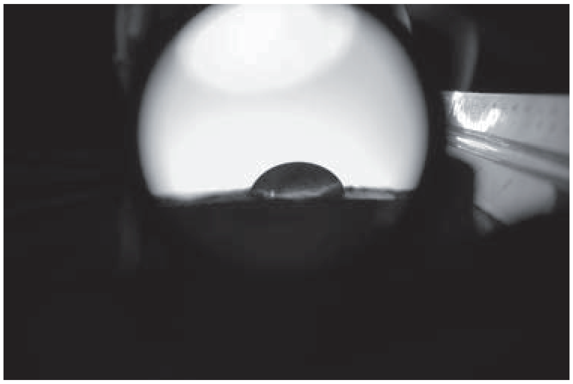
Control 3, Pre-Weathering



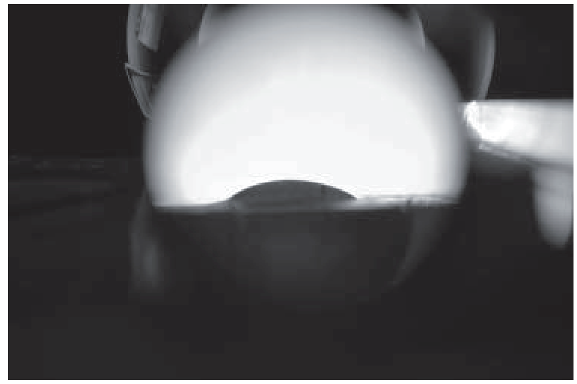
Control 3, Post-Weathering

Testing Images for Contact Angles:

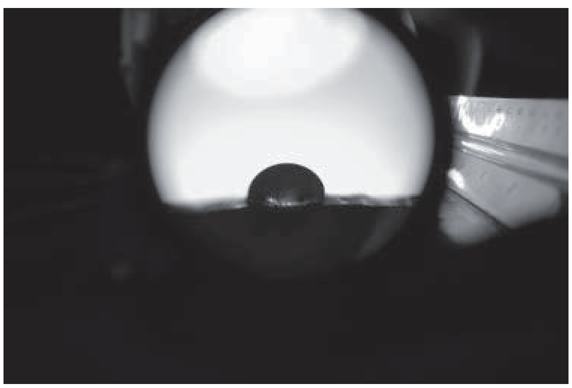
Control:



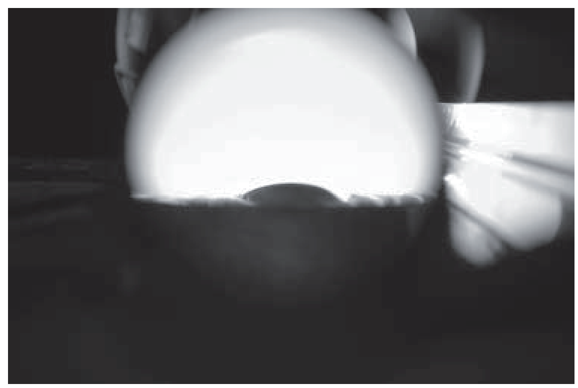
Control 4, Pre-Weathering



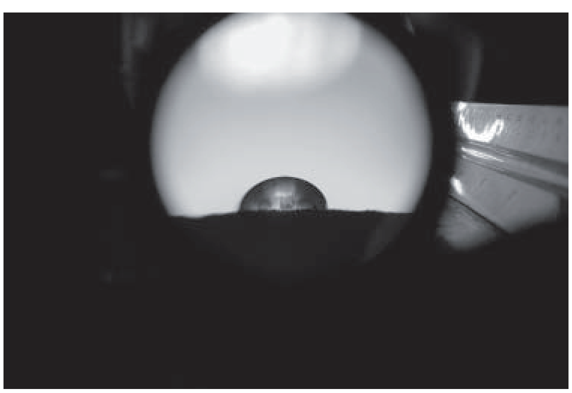
Control 4, Post-Weathering



Control 5, Pre-Weathering



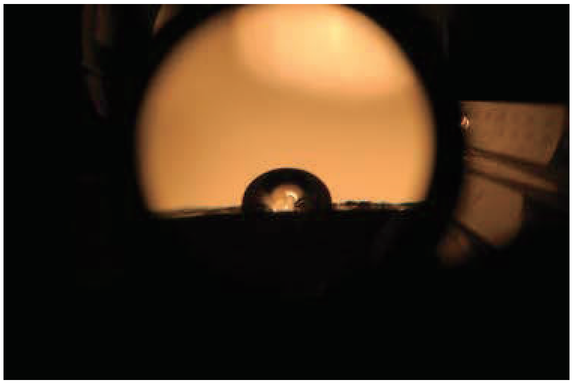
Control 5, Post-Weathering



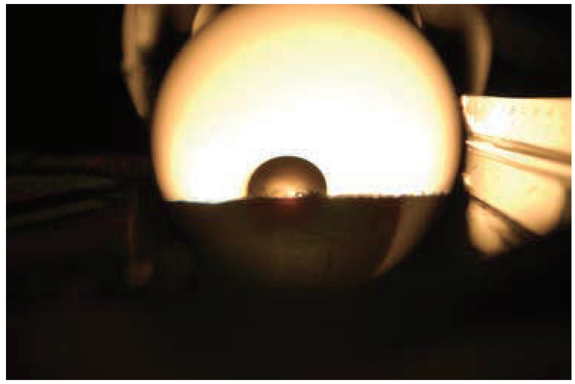
Control 6, Pre-Weathering

Control 6, Post-Weathering

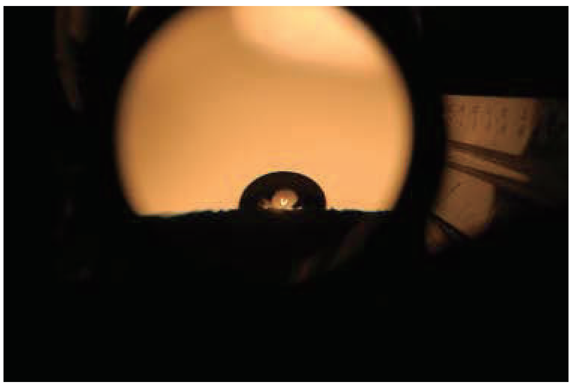
Testing Images for Contact Angles:
Allbäck Boiled Organic Linseed Oil:



Linseed Oil 1, Pre-Weathering

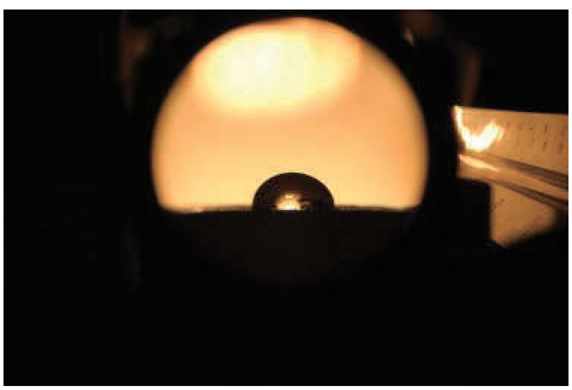


Linseed Oil 1, Post-Weathering

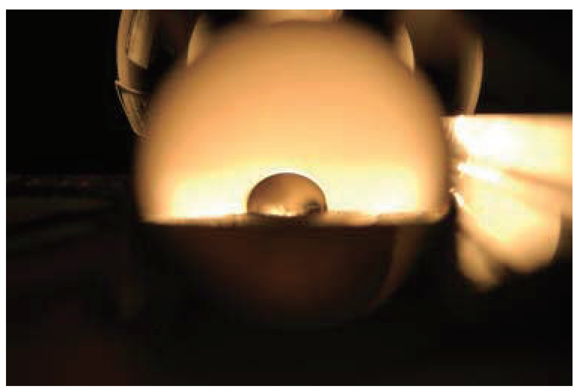


Linseed Oil 2, Pre-Weathering

Linseed Oil 2, Post-Weathering

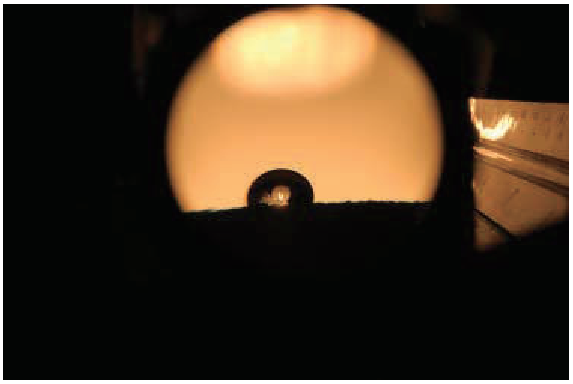


Linseed Oil 3, Pre-Weathering



Linseed Oil 3, Post-Weathering

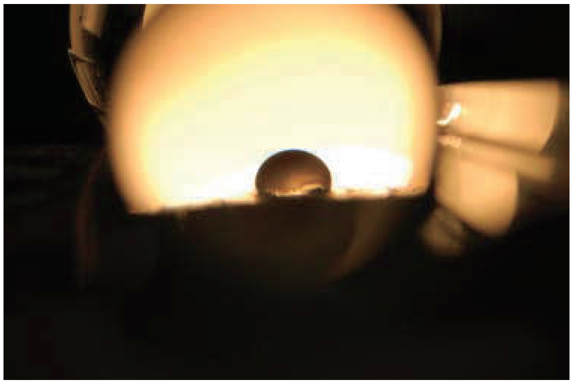
Testing Images for Contact Angles:
Allbäck Boiled Organic Linseed Oil:



Linseed Oil 4, Pre-Weathering

Linseed Oil 4, Post-Weathering

Linseed Oil 5, Pre-Weathering

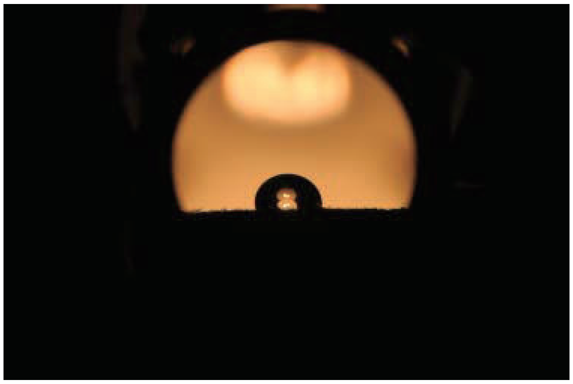


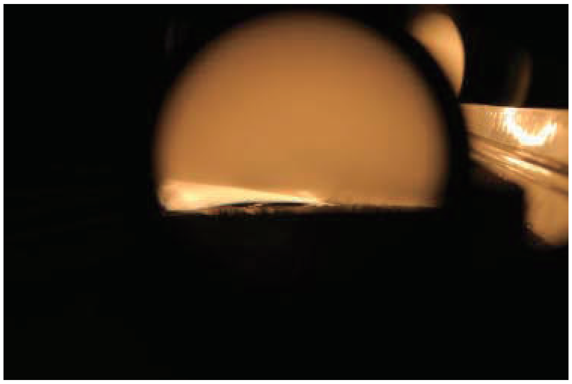
Linseed Oil 5, Post-Weathering

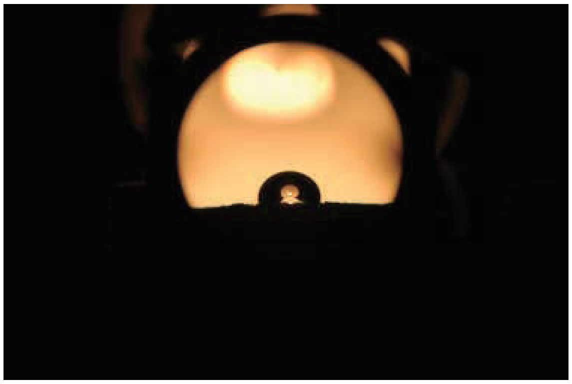
Linseed Oil 6, Pre-Weathering

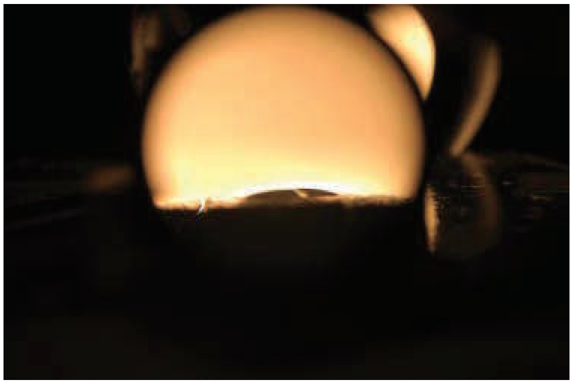
Linseed Oil 6, Post-Weathering

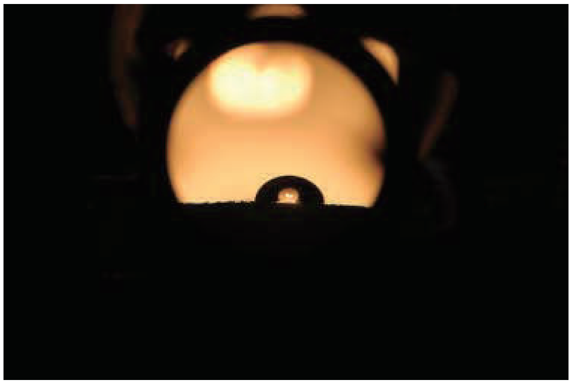
Testing Images for Contact Angles:
Paraffin and Mineral Spirits:


Paraffin and Mineral Spirits 1, Pre-Weathering


Paraffin and Mineral Spirits 1, Post-Weathering

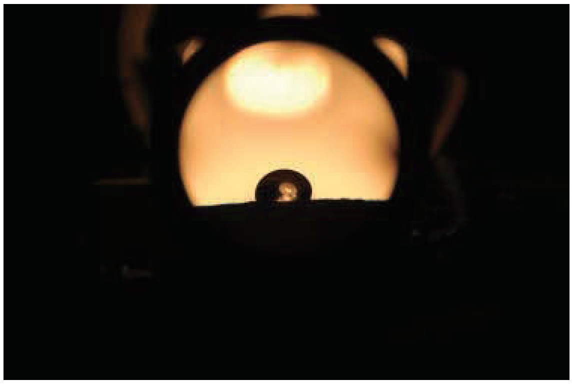

Paraffin and Mineral Spirits 2, Pre-Weathering


Paraffin and Mineral Spirits 2, Post-Weathering


Paraffin and Mineral Spirits 3, Pre-Weathering


Paraffin and Mineral Spirits 3, Post-Weathering

Testing Images for Contact Angles:
Paraffin and Mineral Spirits:

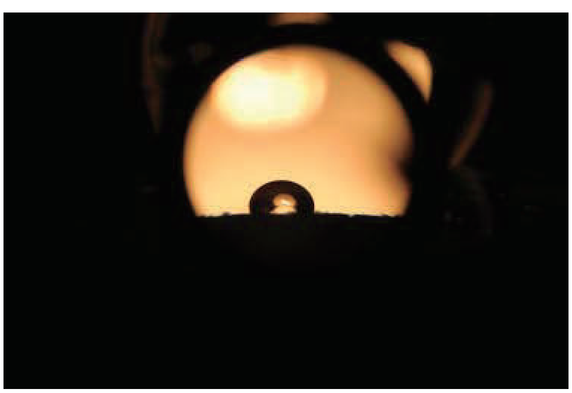


Paraffin and Mineral Spirits 4, Pre-Weathering

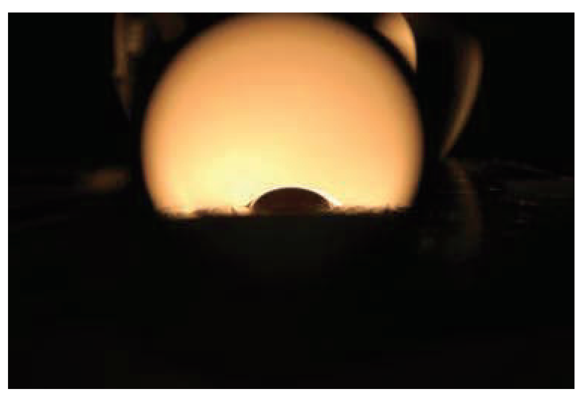
Paraffin and Mineral Spirits 4, Post-Weathering

Paraffin and Mineral Spirits 5, Pre-Weathering

Paraffin and Mineral Spirits 5, Post-Weathering

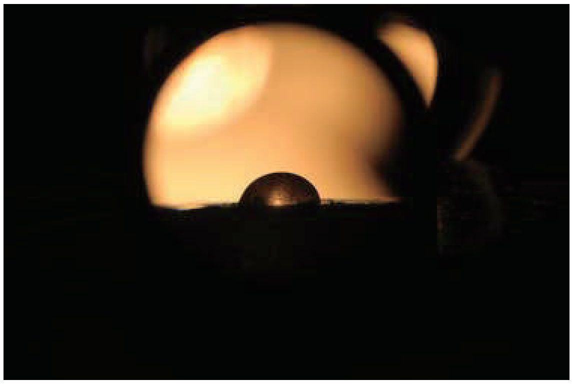


Paraffin and Mineral Spirits 6, Pre-Weathering

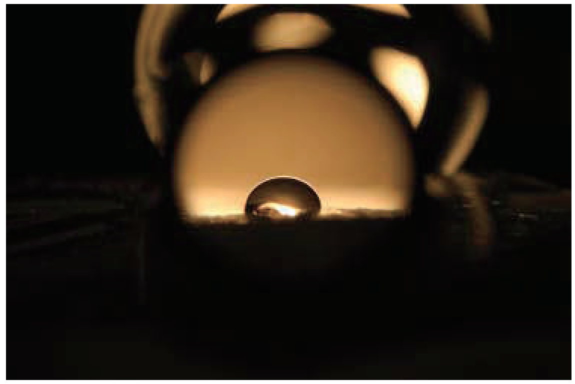


Paraffin and Mineral Spirits 6, Post-Weathering

Testing Images for Contact Angles:
DEFY Extreme Exterior Clear Wood Stain:



DEFY Extreme 1, Pre-Weathering

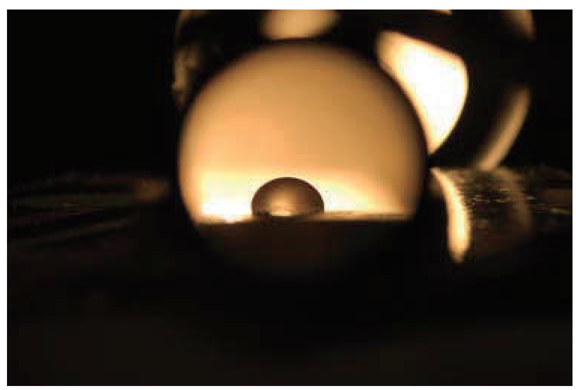


DEFY Extreme 1, Post-Weathering

DEFY Extreme 2, Pre-Weathering

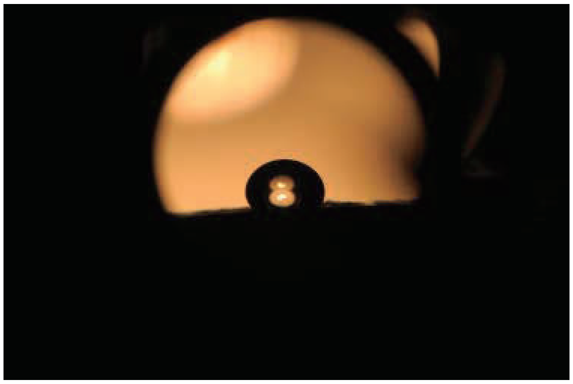
DEFY Extreme 2, Post-Weathering

DEFY Extreme 3, Pre-Weathering



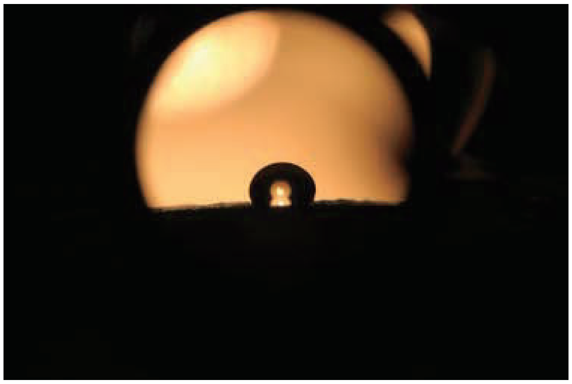
DEFY Extreme 3, Post-Weathering

Testing Images for Contact Angles:
DEFY Extreme Exterior Clear Wood Stain:



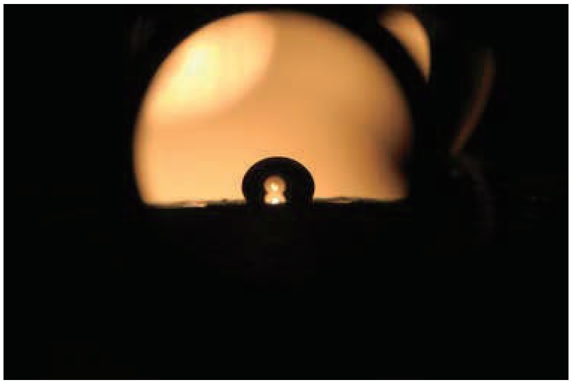
DEFY Extreme 4, Pre-Weathering

DEFY Extreme 4, Post-Weathering



DEFY Extreme 5, Pre-Weathering

DEFY Extreme 5, Post-Weathering



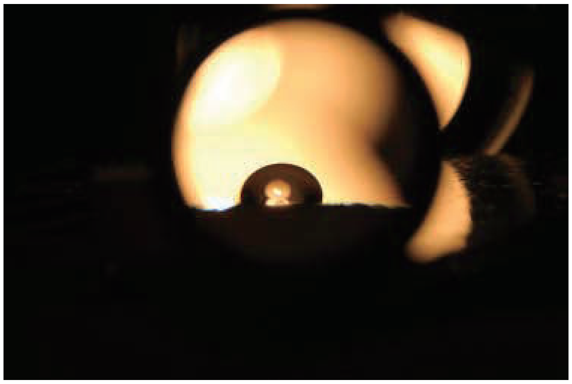
DEFY Extreme 6, Pre-Weathering

DEFY Extreme 6, Post-Weathering

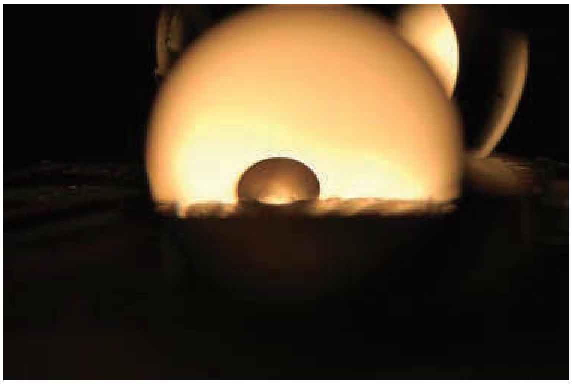
Testing Images for Contact Angles:

Armstrong's Wood Stain for Decks (Natural Tone):

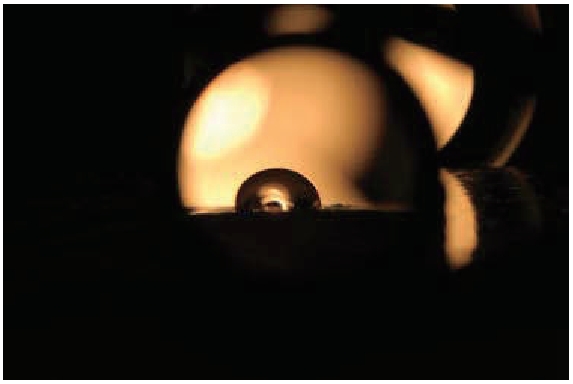
Armstrong's Wood Stain 1, Pre-Weathering



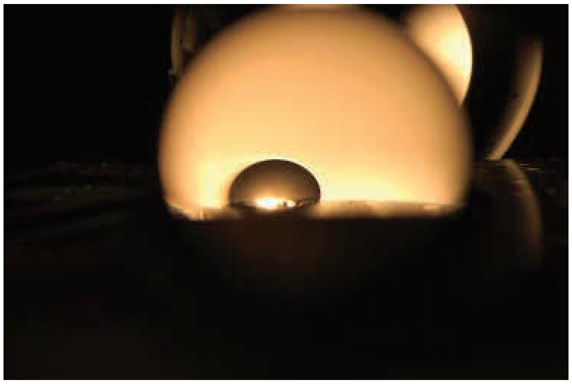
Armstrong's Wood Stain 1, Post-Weathering



Armstrong's Wood Stain 2, Pre-Weathering



Armstrong's Wood Stain 2, Post-Weathering



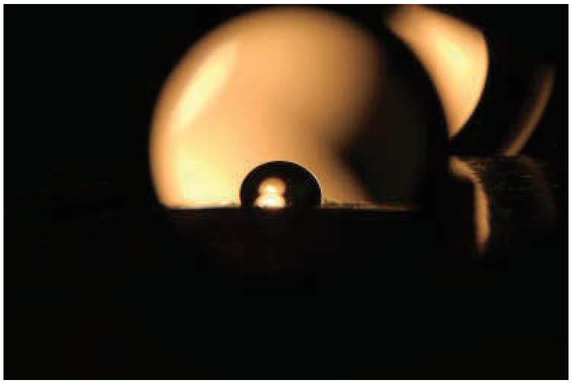
Armstrong's Wood Stain 3, Pre-Weathering

Armstrong's Wood Stain 3, Post-Weathering

Testing Images for Contact Angles:

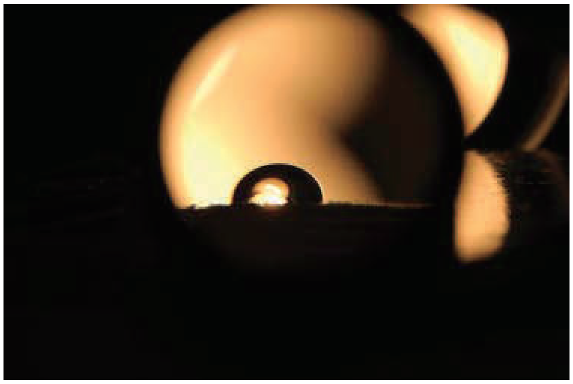
Armstrong's Wood Stain for Decks (Natural Tone):

Armstrong's Wood Stain 4, Pre-Weathering

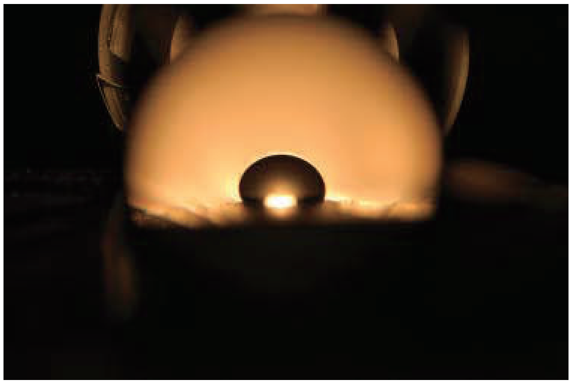


Armstrong's Wood Stain 4, Post-Weathering

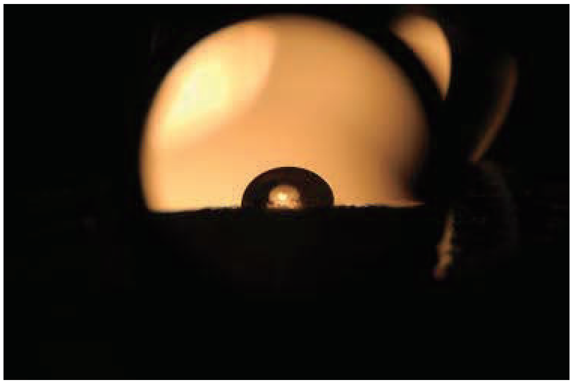
Armstrong's Wood Stain 5, Pre-Weathering



Armstrong's Wood Stain 5, Post-Weathering

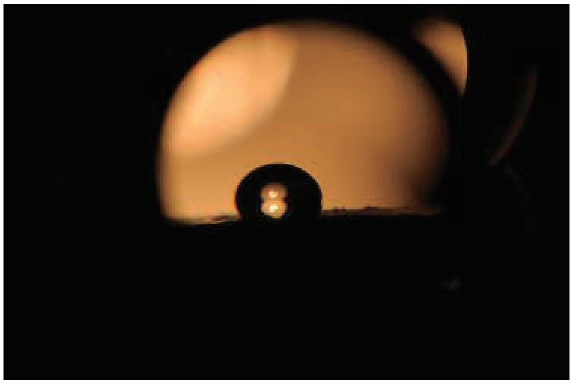


Armstrong's Wood Stain 6, Pre-Weathering



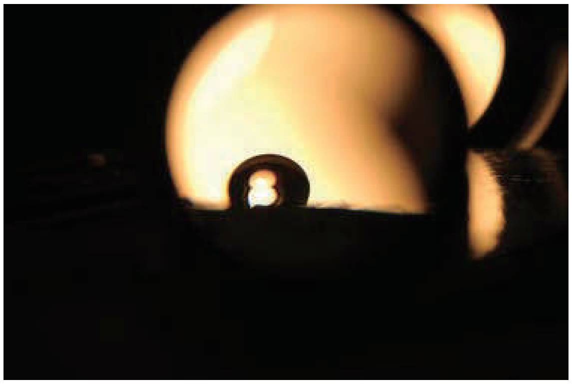
Armstrong's Wood Stain 6, Post-Weathering

Testing Images for Contact Angles:
TWP 1500 Natural Stain (Natural Tone):

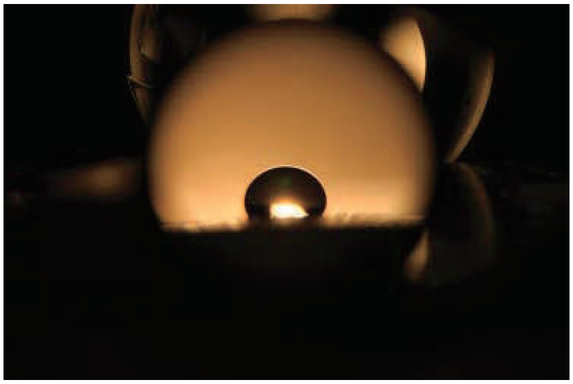


TWP 1500 1, Pre-Weathering

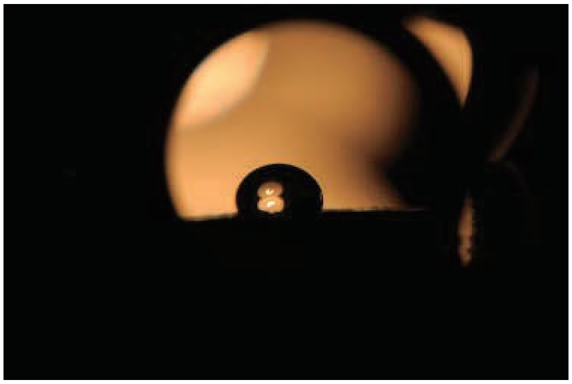
TWP 1500 1, Post-Weathering



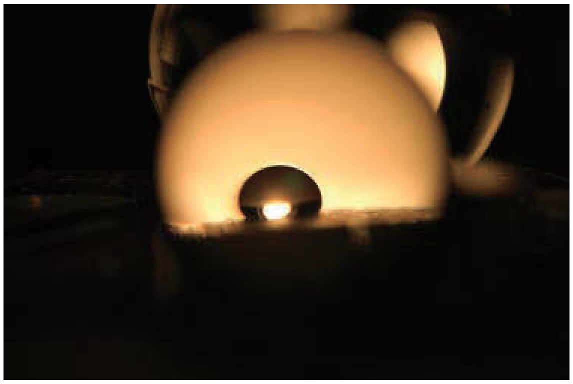
TWP 1500 2, Pre-Weathering



TWP 1500 2, Post-Weathering

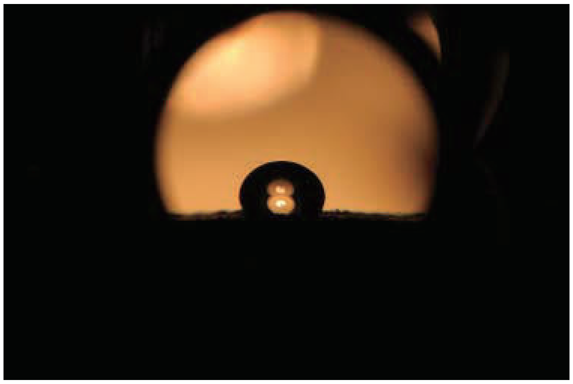


TWP 1500 3, Pre-Weathering



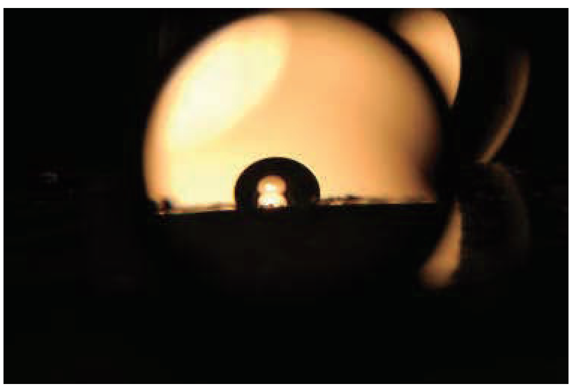
TWP 1500 3, Post-Weathering

Testing Images for Contact Angles:
TWP 1500 Natural Stain (Natural Tone):

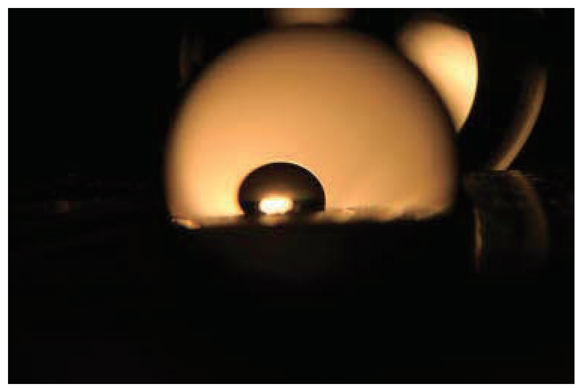


TWP 1500 4, Pre-Weathering

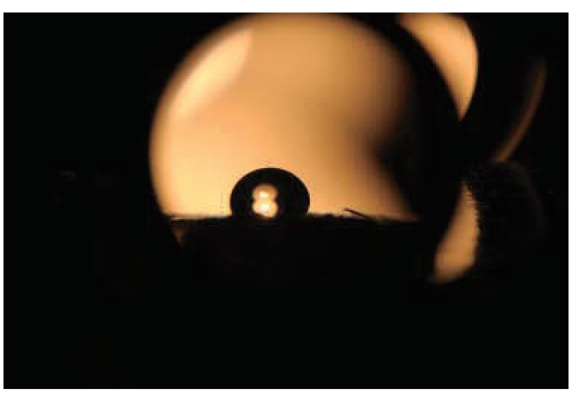
TWP 1500 4, Post-Weathering



TWP 1500 5, Pre-Weathering



TWP 1500 5, Post-Weathering

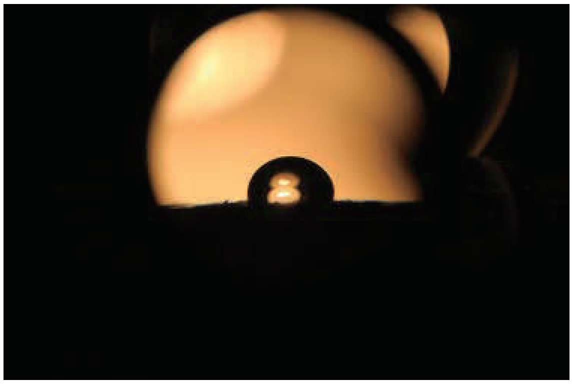


TWP 1500 6, Pre-Weathering

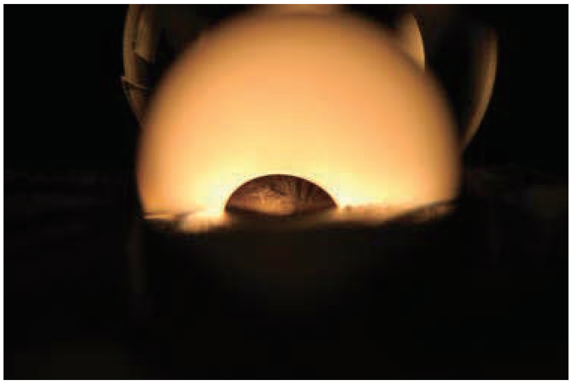
TWP 1500 6, Post-Weathering

Testing Images for Contact Angles:

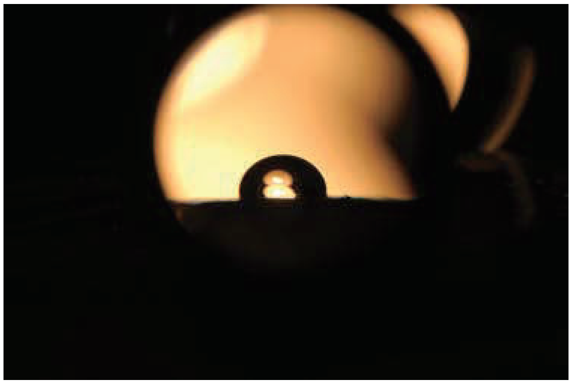
Flood CWF UV-5 Penetrating Wood Finish for Fences, Decks, and Siding (Natural Tone (Clear)):



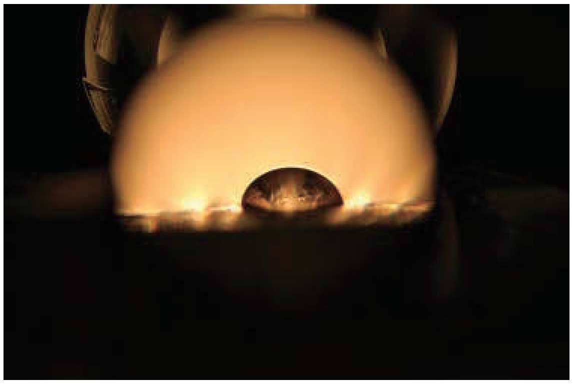
Flood CWF UV-5 1, Pre-Weathering



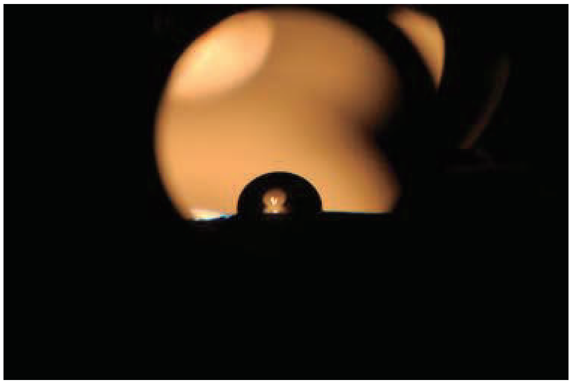
Flood CWF UV-5 1, Post-Weathering



Flood CWF UV-5 2, Pre-Weathering



Flood CWF UV-5 2, Post-Weathering

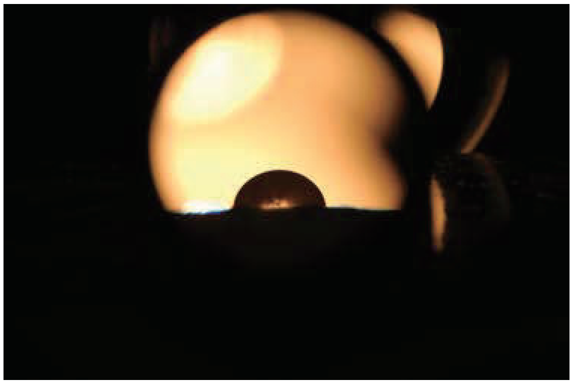


Flood CWF UV-5 3, Pre-Weathering

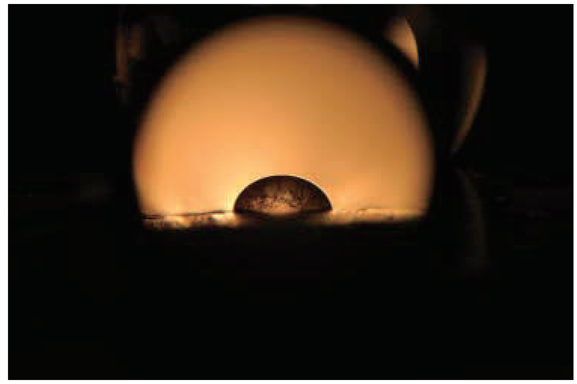
Flood CWF UV-5 3, Post-Weathering

Testing Images for Contact Angles:

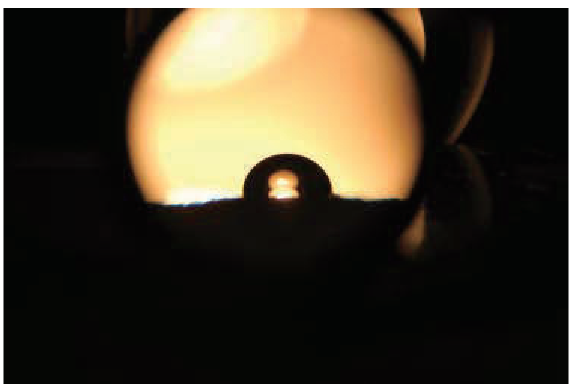
Flood CWF UV-5 Penetrating Wood Finish for Fences, Decks, and Siding (Natural Tone (Clear)):



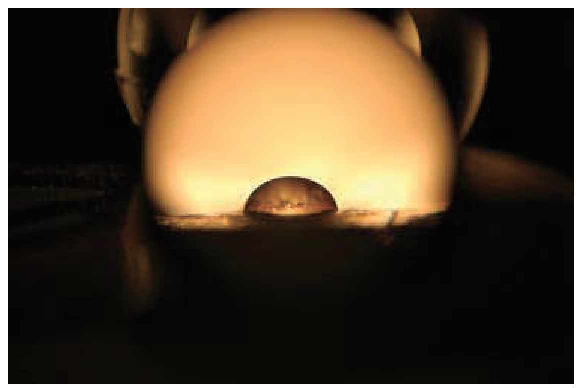
Flood CWF UV-5 4, Pre-Weathering



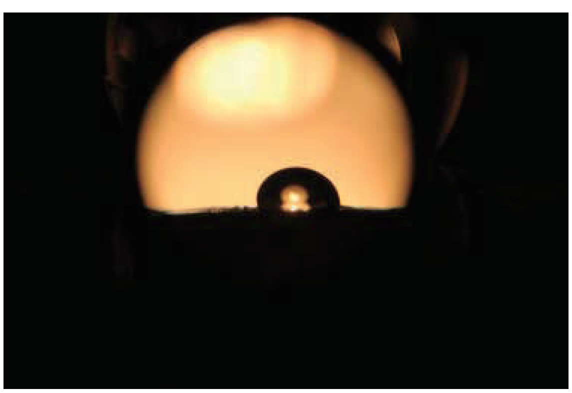
Flood CWF UV-5 4, Post-Weathering



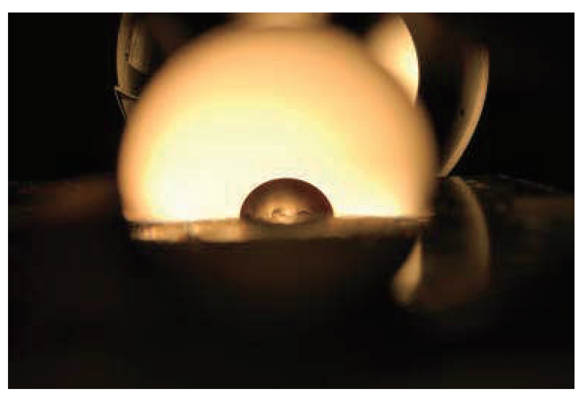
Flood CWF UV-5 5, Pre-Weathering



Flood CWF UV-5 5, Post-Weathering

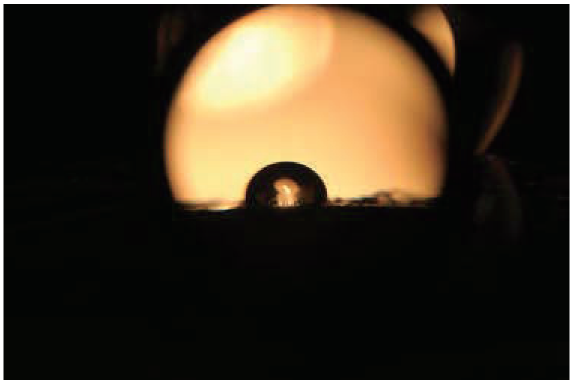


Flood CWF UV-5 6, Pre-Weathering

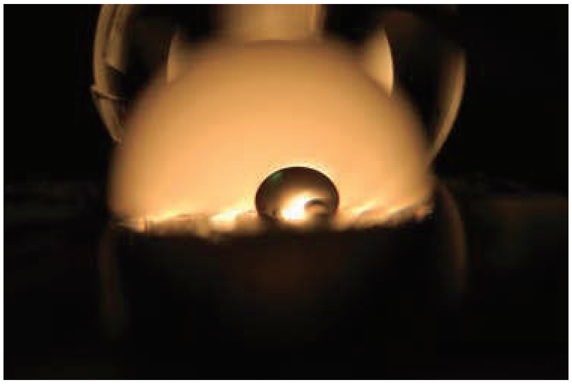


Flood CWF UV-5 6, Post-Weathering

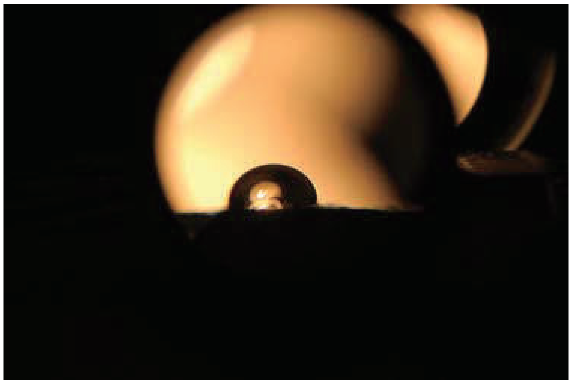
Testing Images for Contact Angles:
Messmer's U.V. Plus Exterior Wood Finish (Natural):



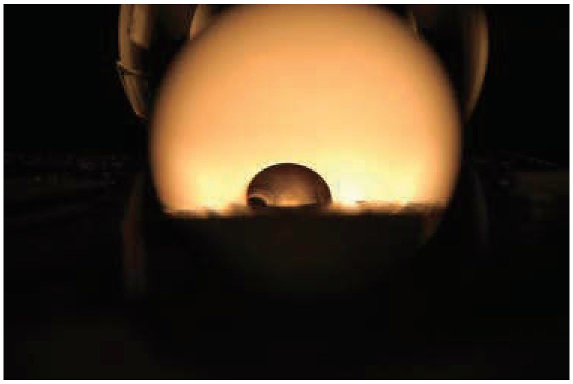
Messmer's UV Plus 1, Pre-Weathering



Messmer's UV Plus 1, Post-Weathering



Messmer's UV Plus 2, Pre-Weathering

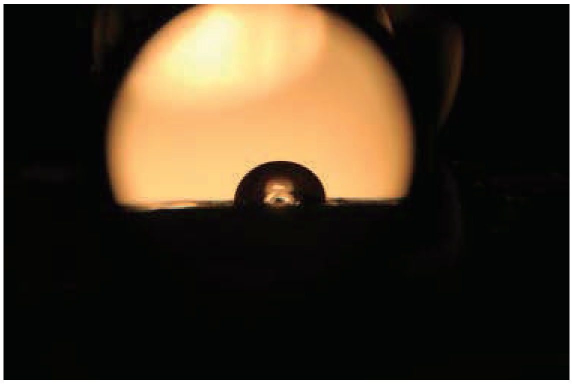


Messmer's UV Plus 2, Post-Weathering

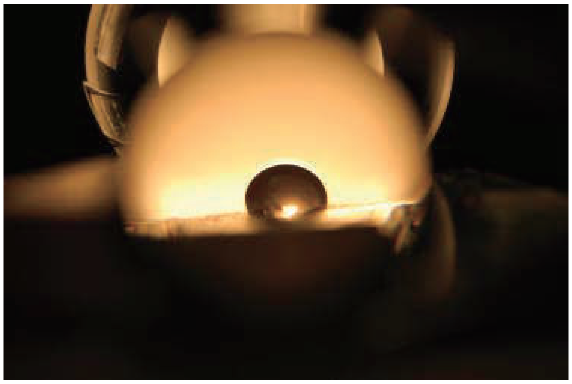
Messmer's UV Plus 3, Pre-Weathering

Messmer's UV Plus 3, Post-Weathering

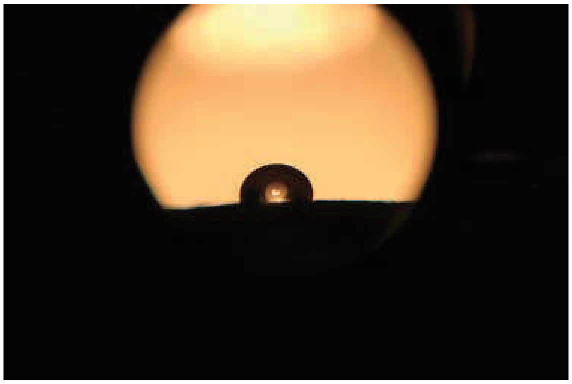
Testing Images for Contact Angles:
Messmer's U.V. Plus Exterior Wood Finish (Natural):



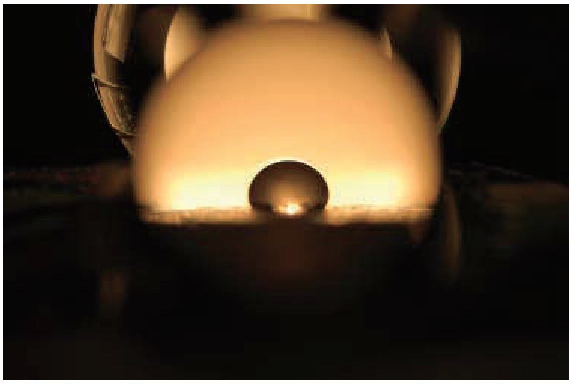
Messmer's UV Plus 4, Pre-Weathering



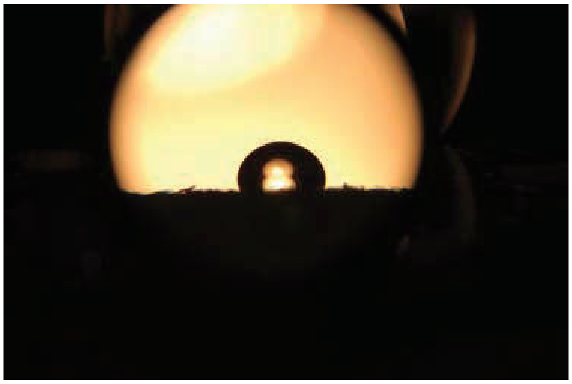
Messmer's UV Plus 4, Post-Weathering



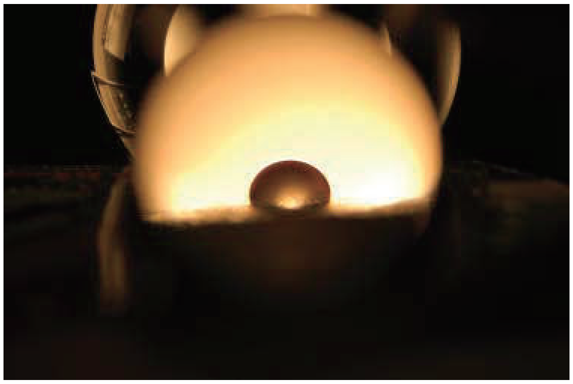
Messmer's UV Plus 5, Pre-Weathering



Messmer's UV Plus 5, Post-Weathering



Messmer's UV Plus 6, Pre-Weathering



Messmer's UV Plus 6, Post-Weathering

Appendix F - Photographs of Samples

Sample Changes Over Time:

0 Hours (Pre-Weathering)

Control / Linseed / Paraffin and Mineral Spirits

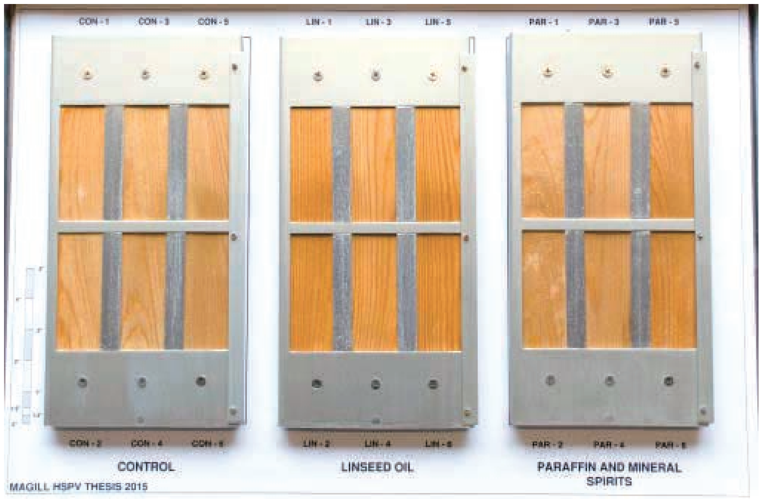
100 Hours

Control / Linseed / Paraffin and Mineral Spirits

200 Hours

Control / Linseed / Paraffin and Mineral Spirits

Sample Changes Over Time:



300 Hours
Control / Linseed / Paraffin and Mineral Spirits

400 Hours

Control / Linseed / Paraffin and Mineral Spirits

500 Hours

Control / Linseed / Paraffin and Mineral Spirits

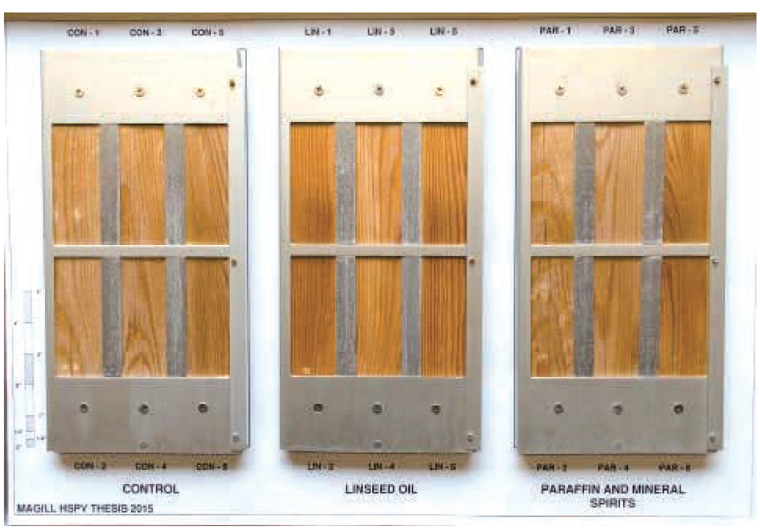
Sample Changes Over Time:

600 Hours

Control / Linseed / Paraffin and Mineral Spirits

700 Hours

Control / Linseed / Paraffin and Mineral Spirits



800 Hours

Control / Linseed / Paraffin and Mineral Spirits

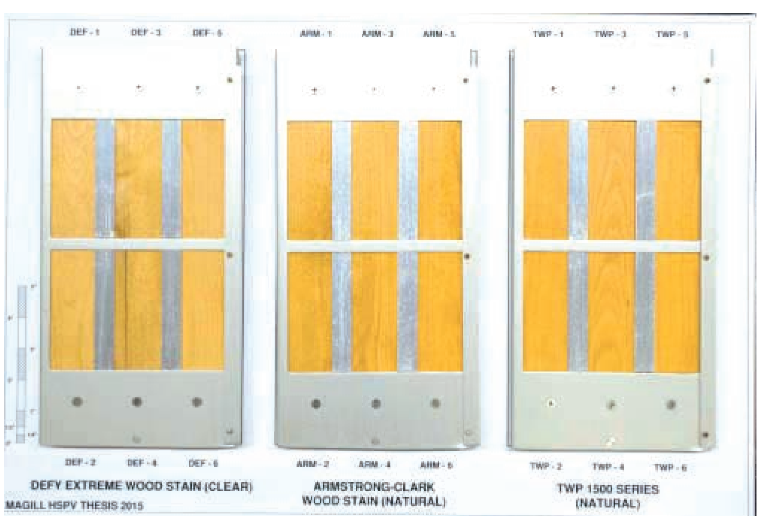
Sample Changes Over Time:

0 Hours (Pre-Weathering)

DEFY / Armstrong / TWP 1500

100 Hours

DEFY / Armstrong / TWP 1500



200 Hours

DEFY / Armstrong / TWP 1500

Sample Changes Over Time:

300 Hours

DEFY / Armstrong / TWP 1500

400 Hours

DEFY / Armstrong / TWP 1500

500 Hours

DEFY / Armstrong / TWP 1500

Sample Changes Over Time:

600 Hours

DEFY / Armstrong / TWP 1500

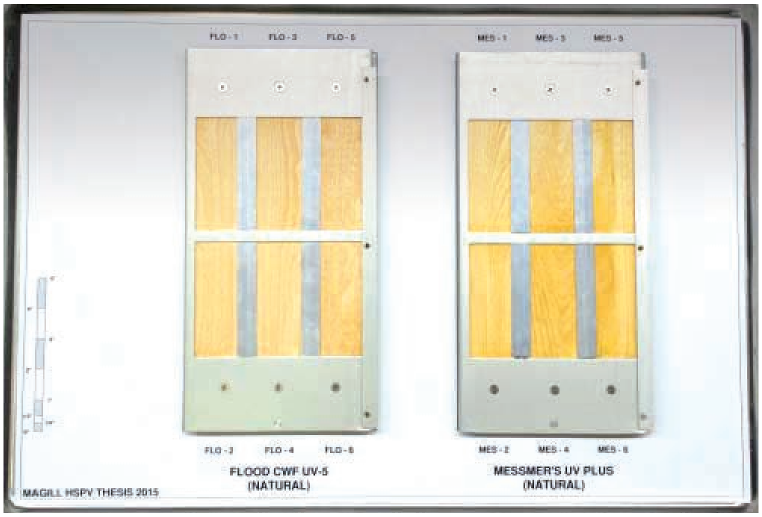
700 Hours

DEFY / Armstrong / TWP 1500

800 Hours

DEFY / Armstrong / TWP 1500

Sample Changes Over Time:



0 Hours (Pre-Weathering)

Flood / Messmer's

100 Hours

Flood / Messmer's

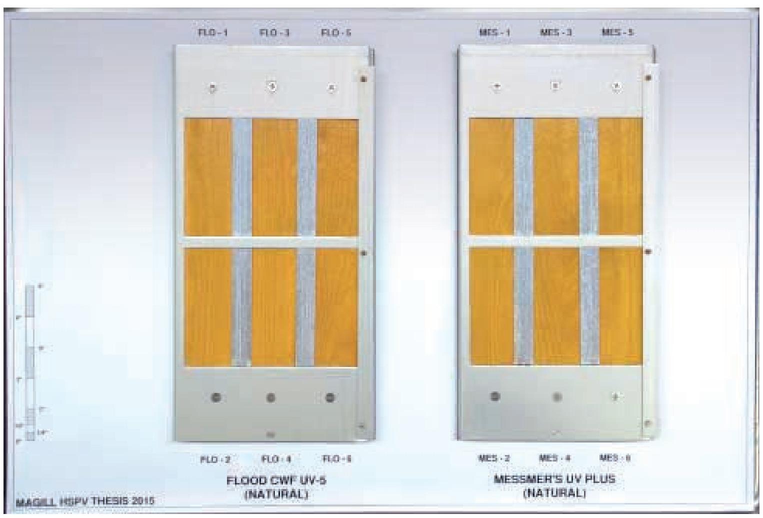
200 Hours

Flood / Messmer's

Sample Changes Over Time:

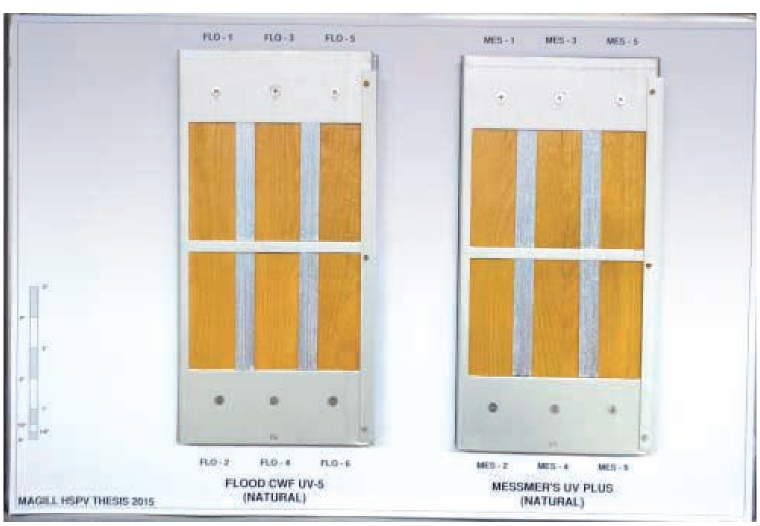
300 Hours

Flood / Messmer’s



400 Hours

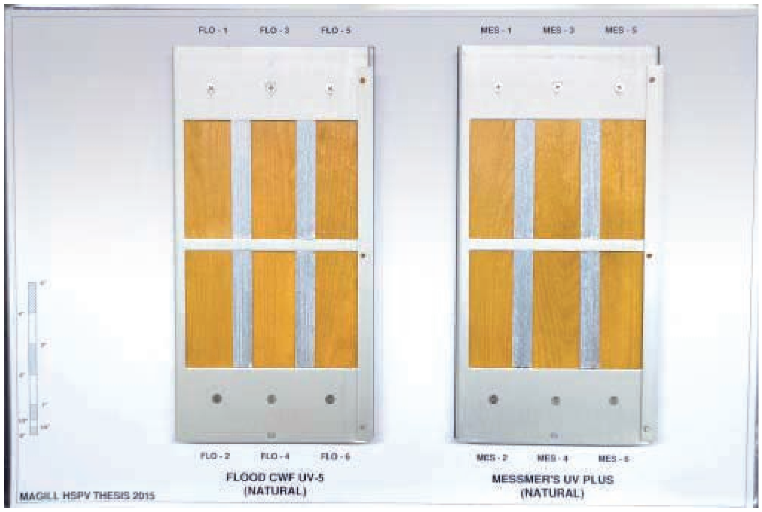
Flood / Messmer’s



500 Hours

Flood / Messmer’s

Sample Changes Over Time:



600 Hours

Flood / Messmer's

700 Hours

Flood / Messmer's

800 Hours

Flood / Messmer's

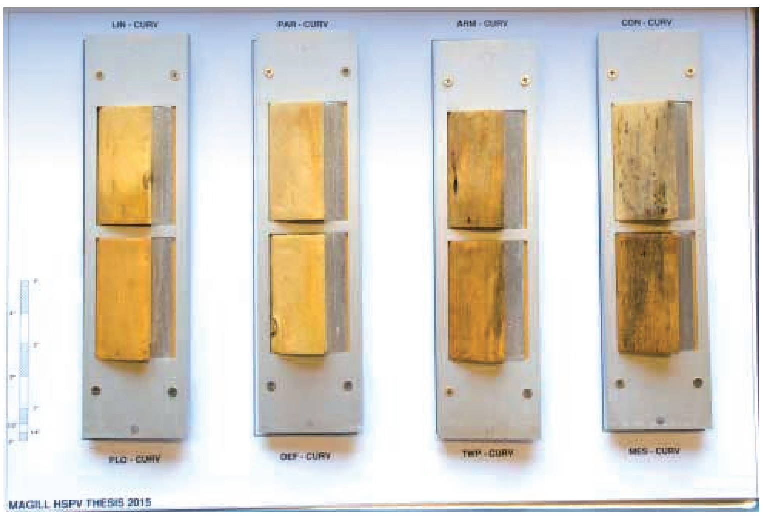
Sample Changes Over Time:

0 Hours (Pre-Weathering)

Curved Samples:

Top (left to right): Linseed / Paraffin / Armstrong / Control

Bottom (left to right): Flood / DEFY / TWP 1500 / Messmer's



100 Hours

Curved Samples:

Top (left to right): Linseed / Paraffin / Armstrong / Control

Bottom (left to right): Flood / DEFY / TWP 1500 / Messmer's

200 Hours

Curved Samples:

Top (left to right): Linseed / Paraffin / Armstrong / Control

Bottom (left to right): Flood / DEFY / TWP 1500 / Messmer's

Sample Changes Over Time:

300 Hours

Curved Samples:

Top (left to right): Linseed / Paraffin / Armstrong / Control

Bottom (left to right): Flood / DEFY / TWP 1500 / Messmer's

400 Hours

Curved Samples:

Top (left to right): Linseed / Paraffin / Armstrong / Control

Bottom (left to right): Flood / DEFY / TWP 1500 / Messmer's

500 Hours

Curved Samples:

Top (left to right): Linseed / Paraffin / Armstrong / Control

Bottom (left to right): Flood / DEFY / TWP 1500 / Messmer's

Sample Changes Over Time:

600 Hours

Curved Samples:

Top (left to right): Linseed / Paraffin / Armstrong / Control

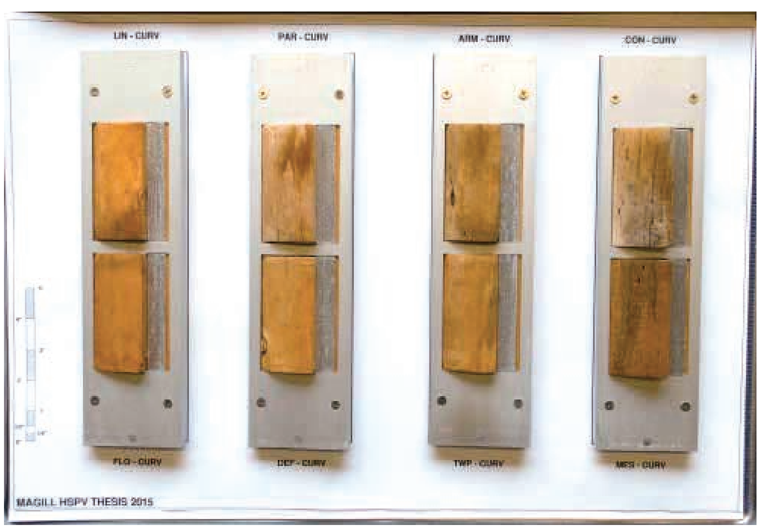
Bottom (left to right): Flood / DEFY / TWP 1500 / Messmer's

700 Hours

Curved Samples:

Top (left to right): Linseed / Paraffin / Armstrong / Control

Bottom (left to right): Flood / DEFY / TWP 1500 / Messmer's



800 Hours

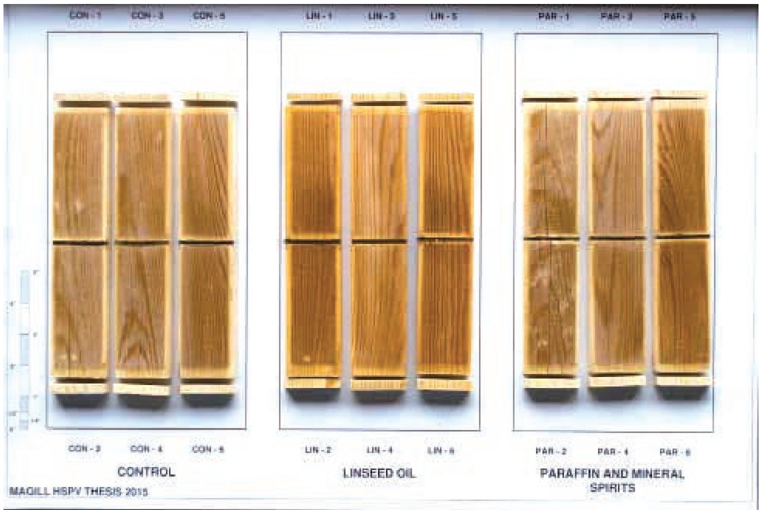
Curved Samples:

Top (left to right): Linseed / Paraffin / Armstrong / Control

Bottom (left to right): Flood / DEFY / TWP 1500 / Messmer's

Sample Changes Over Time:

Samples after weathering with sections cut off of ends pre-weathering for comparison:

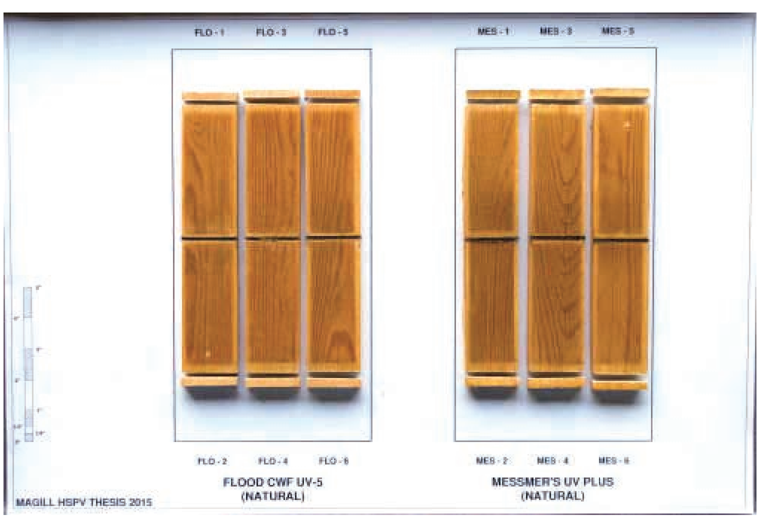


800 Hours (Post-Weathering)

Control / Linseed / Paraffin and Mineral Spirits

800 Hours (Post-Weathering)

DEFY / Armstrong / TWP 1500

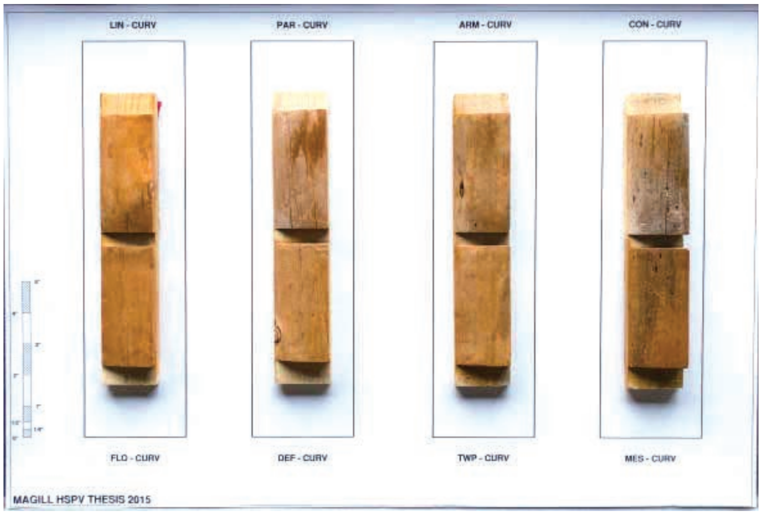


800 Hours (Post-Weathering)

Flood / Messmer's

Sample Changes Over Time:

Samples after weathering with sections cut off of ends pre-weathering for comparison:



800 Hours (Post-Weathering)

Curved Samples:

Top (left to right): Linseed / Paraffin / Armstrong / Control

Bottom (left to right): Flood / DEFY / TWP 1500 / Messmer's

Sample Changes Over Time:

Samples after weathering with sections cut off of ends pre-weathering for comparison:

Control, 800 Hours (Post-Weathering)

Linseed Oil, 800 Hours (Post-Weathering)

Paraffin and Mineral Spirits, 800 Hours (Post-Weathering)

DEFY Extreme, 800 Hours (Post-Weathering)

Sample Changes Over Time:

Samples after weathering with sections cut off of ends pre-weathering for comparison:

1 3 5

2 4 6

Armstrong's Wood Stain, 800 Hours (Post-Weathering)

1 3 5

2 4 6

TWP 1500, 800 Hours (Post-Weathering)

1 3 5

2 4 6

Flood CWF UV-5, 800 Hours (Post-Weathering)

1 3 5

2 4 6

Messmer's UV Plus, 800 Hours (Post-Weathering)

Sample Changes Over Time:

Curved samples after weathering for 800 hours:

Linseed Oil

Flood CWF UV-5

Paraffin & Mineral Spirits

DEFY Extreme

Armstrong's Wood Stain

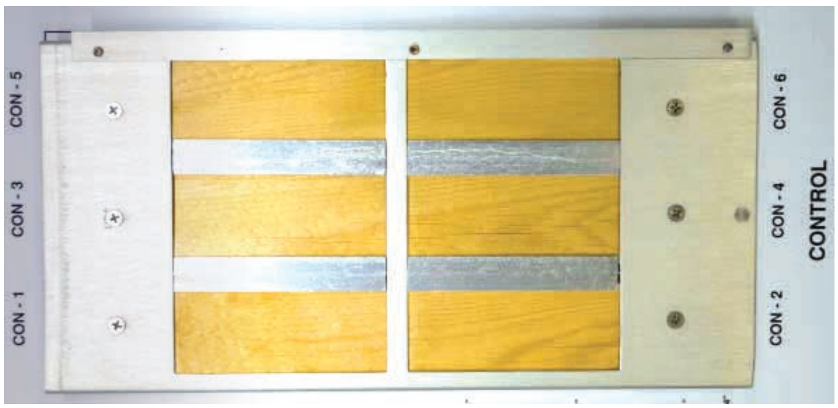
TWP 1500

Control

Messmer's UV Plus

Sample Changes Over Time:
Control:

300 Hours



200 Hours

100 Hours

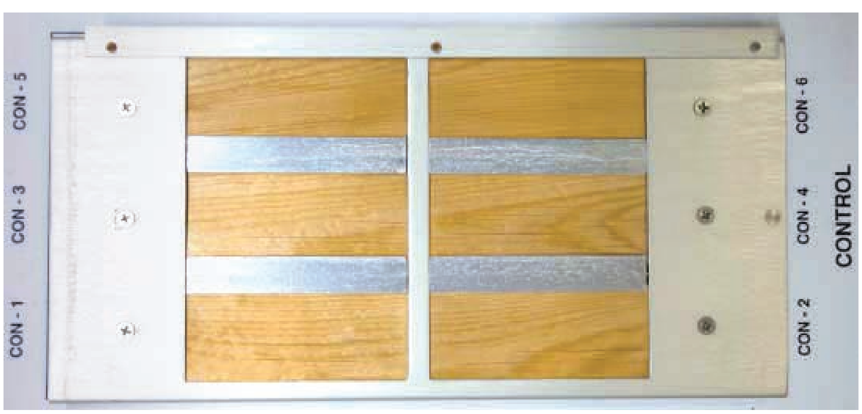
0 Hours (Pre-Weathering)

Sample Changes Over Time:
Control:

700 Hours

600 Hours

500 Hours



400 Hours

Sample Changes Over Time:
Control:

800 Hours (Post-Weathering, Out of Brackets, with Unweathered Sample Cut-offs for Comparison)

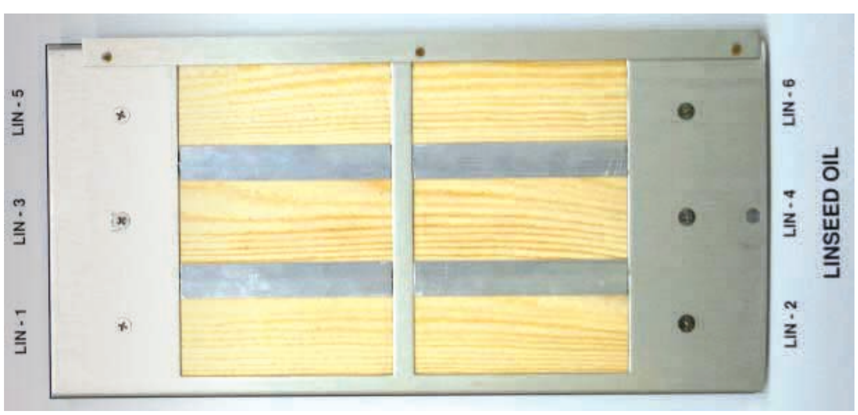
800 Hours (Post-Weathering)

Sample Changes Over Time:
Allbäck Boiled Organic Linseed Oil:

300 Hours

200 Hours

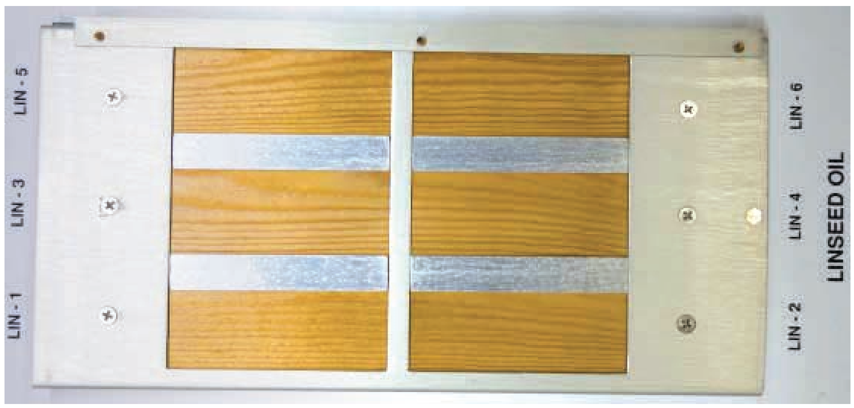
100 Hours



0 Hours (Pre-Weathering)

Sample Changes Over Time:
Allbäck Boiled Organic Linseed Oil:

700 Hours



600 Hours

500 Hours

400 Hours

Sample Changes Over Time:
Allbäck Boiled Organic Linseed Oil:

800 Hours (Post-Weathering, Out of Brackets, with Unweathered Sample Cut-offs for Comparison)

800 Hours (Post-Weathering)

Sample Changes Over Time:
Paraffin and Mineral Spirits:

300 Hours

200 Hours

100 Hours

0 Hours (Pre-Weathering)

Sample Changes Over Time:
Paraffin and Mineral Spirits:

700 Hours

600 Hours

500 Hours

400 Hours

Sample Changes Over Time:
Paraffin and Mineral Spirits:

800 Hours (Post-Weathering, Out of Brackets, with Unweathered Sample Cut-offs for Comparison)

800 Hours (Post-Weathering)

Sample Changes Over Time:
DEFY Extreme Exterior Clear Wood Stain:

300 Hours

200 Hours

100 Hours

0 Hours (Pre-Weathering)

Sample Changes Over Time:
DEFY Extreme Exterior Clear Wood Stain:

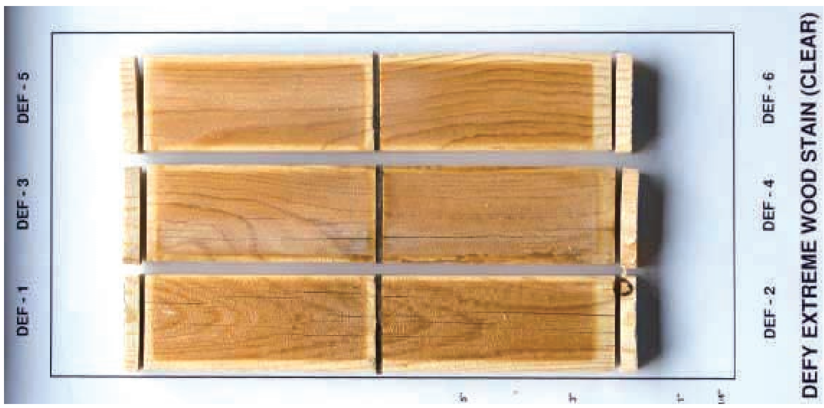
700 Hours

600 Hours

500 Hours

400 Hours

Sample Changes Over Time:
DEFY Extreme Exterior Clear Wood Stain:

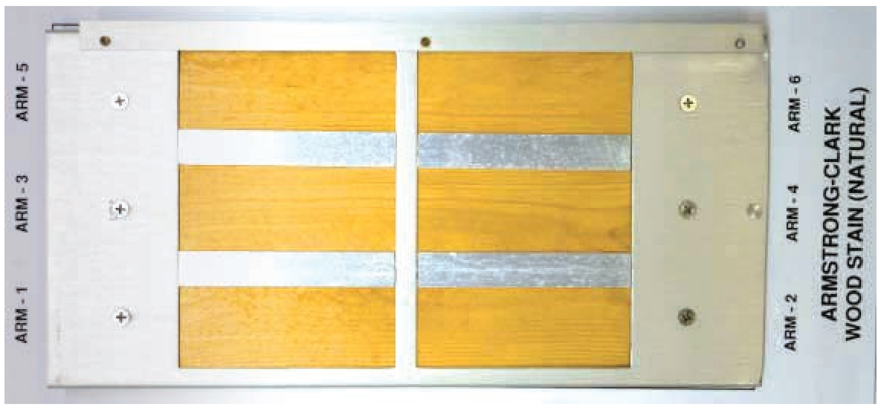


800 Hours (Post-Weathering, Out of Brackets, with Unweathered Sample Cut-offs for Comparison)

800 Hours (Post-Weathering)

Sample Changes Over Time:
Armstrong's Wood Stain for Decks (Natural Tone):

300 Hours

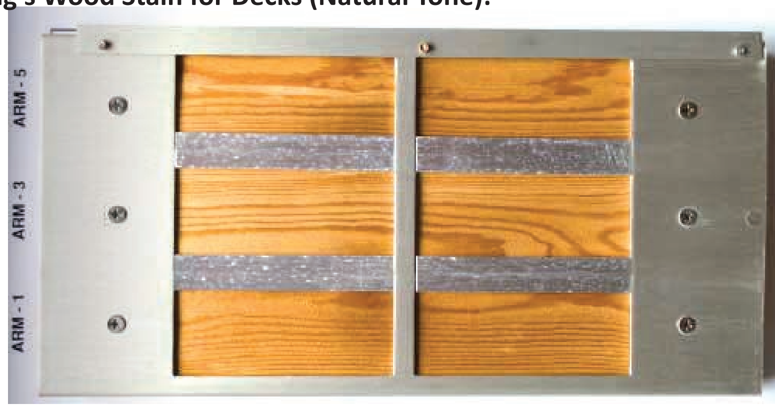


200 Hours

100 Hours

0 Hours (Pre-Weathering)

Sample Changes Over Time:
Armstrong's Wood Stain for Decks (Natural Tone):



700 Hours

600 Hours

500 Hours

400 Hours

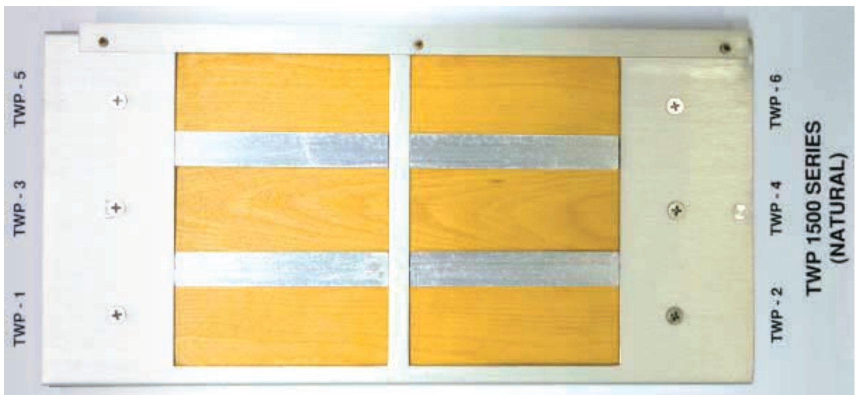
Sample Changes Over Time:
Armstrong's Wood Stain for Decks (Natural Tone):

800 Hours (Post-Weathering, Out of Brackets, with Unweathered Sample Cut-offs for Comparison)

800 Hours (Post-Weathering)

Sample Changes Over Time:
TWP 1500 Natural Stain (Natural Tone):

300 Hours

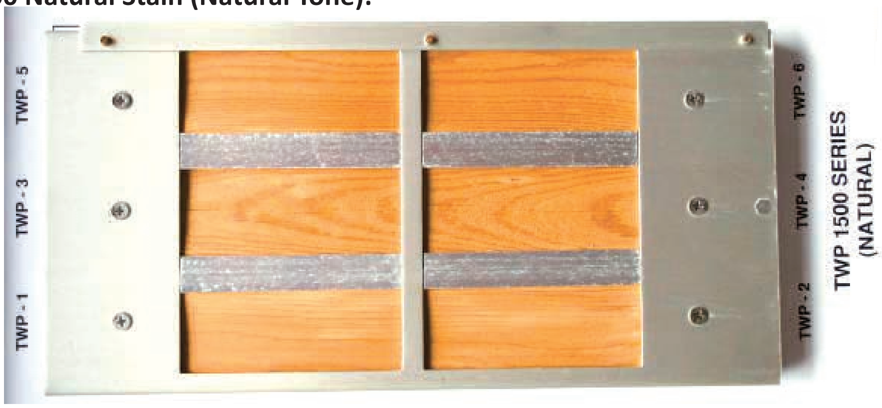


200 Hours

100 Hours

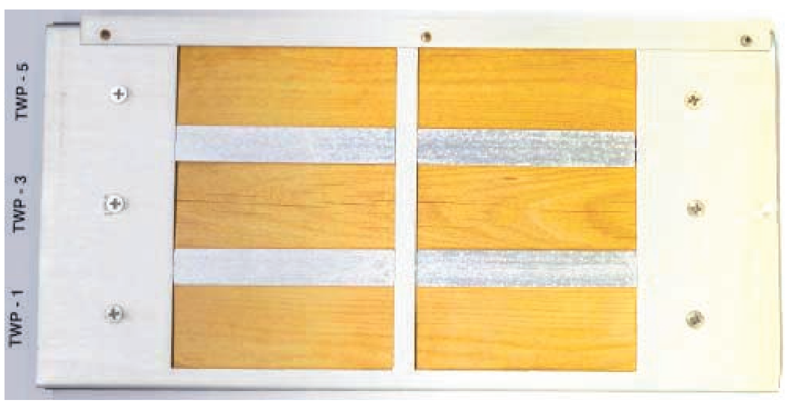
0 Hours (Pre-Weathering)

Sample Changes Over Time:
TWP 1500 Natural Stain (Natural Tone):



700 Hours

600 Hours



500 Hours

400 Hours

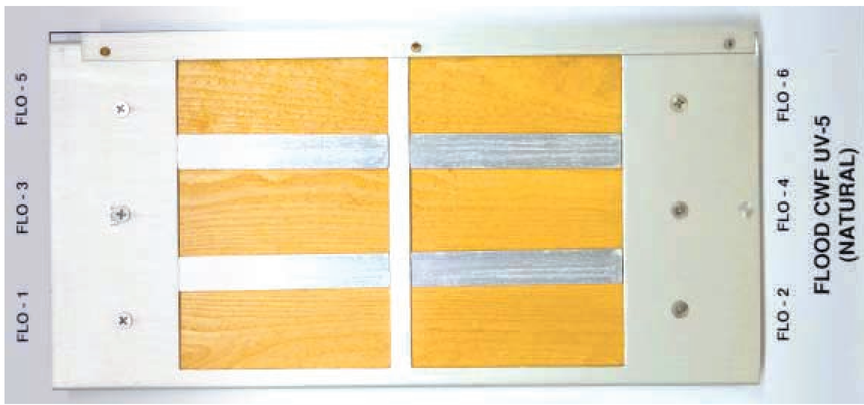
Sample Changes Over Time:
TWP 1500 Natural Stain (Natural Tone):

800 Hours (Post-Weathering)

800 Hours (Post-Weathering, Out of Brackets, with Unweathered Sample Cut-offs for Comparison)

Sample Changes Over Time:
Flood CWF UV-5 Penetrating Wood Finish for Fences, Decks, and Siding (Natural Tone (Clear)):

300 Hours

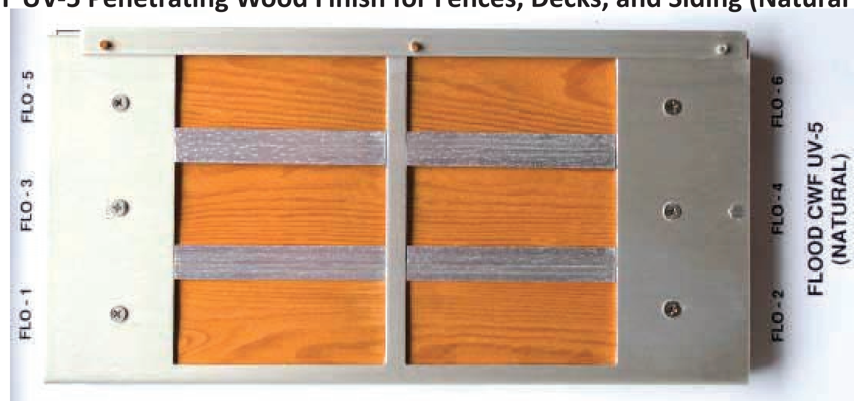


200 Hours

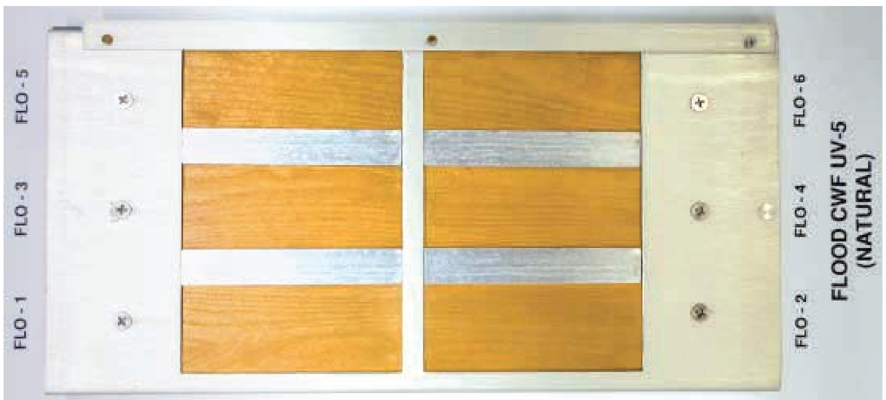
100 Hours

0 Hours (Pre-Weathering)

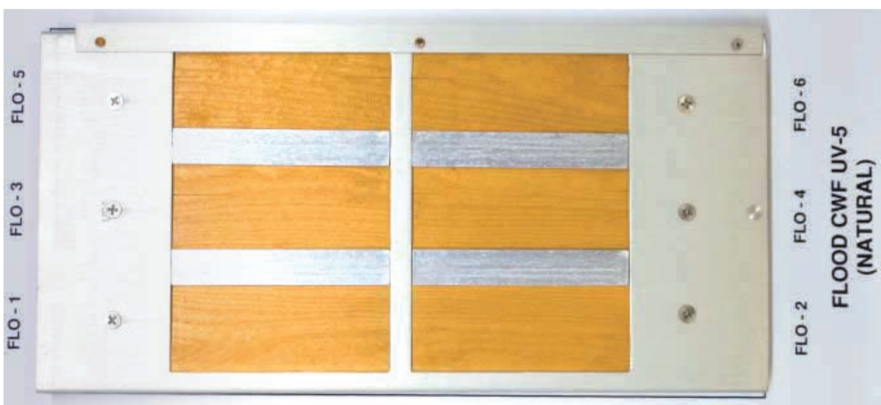
Sample Changes Over Time:
Flood CWF UV-5 Penetrating Wood Finish for Fences, Decks, and Siding (Natural Tone (Clear)):



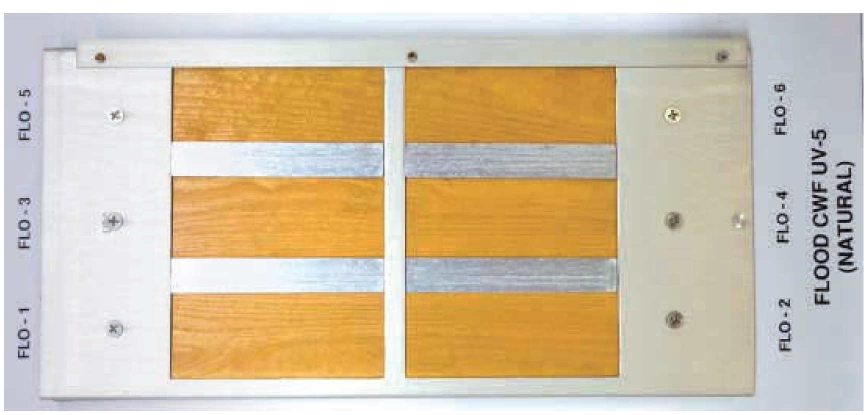
700 Hours



600 Hours



500 Hours



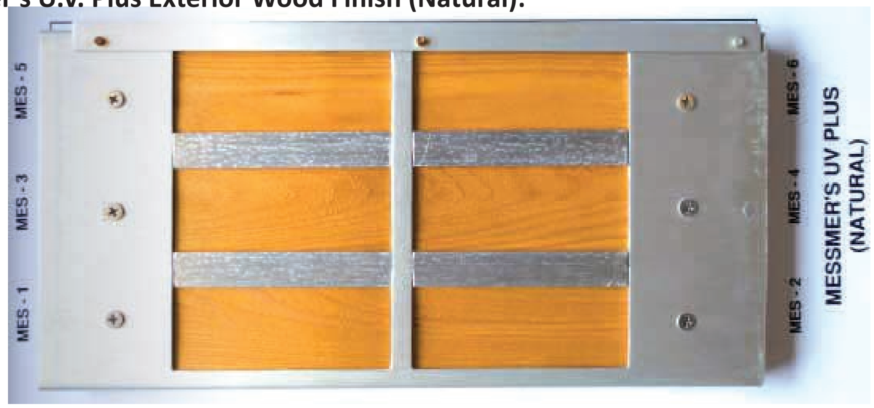
400 Hours

Sample Changes Over Time:
Flood CWF UV-5 Penetrating Wood Finish for Fences, Decks, and Siding (Natural Tone (Clear)):

800 Hours (Post-Weathering, Out of Brackets, with Unweathered Sample Cut-offs for Comparison)

800 Hours (Post-Weathering)

Sample Changes Over Time:
Messmer's U.V. Plus Exterior Wood Finish (Natural):



300 Hours

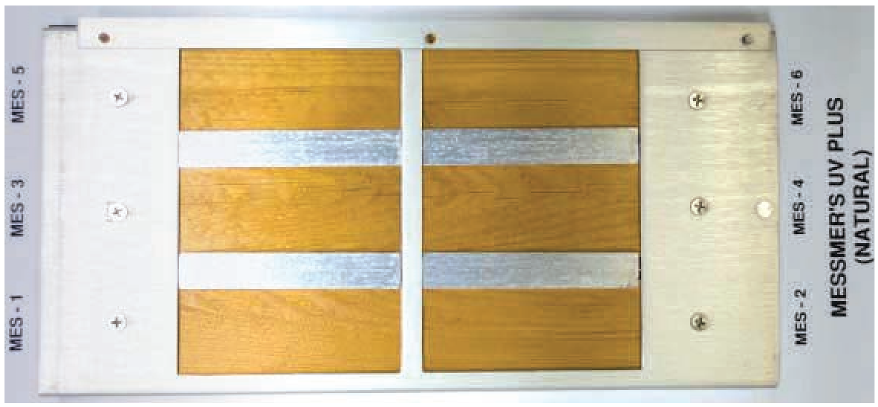
200 Hours

100 Hours

0 Hours (Pre-Weathering)

Sample Changes Over Time:
Messmer's U.V. Plus Exterior Wood Finish (Natural):

700 Hours



600 Hours

500 Hours

400 Hours

Sample Changes Over Time:
Messmer's U.V. Plus Exterior Wood Finish (Natural):

800 Hours (Post-Weathering, Out of Brackets, with Unweathered Sample Cut-offs for Comparison)

800 Hours (Post-Weathering)

Sample Changes Over Time:

Curved Samples (Linseed Oil (Top) and Flood CWF UV-5 (Bottom)):

400 Hours

300 Hours

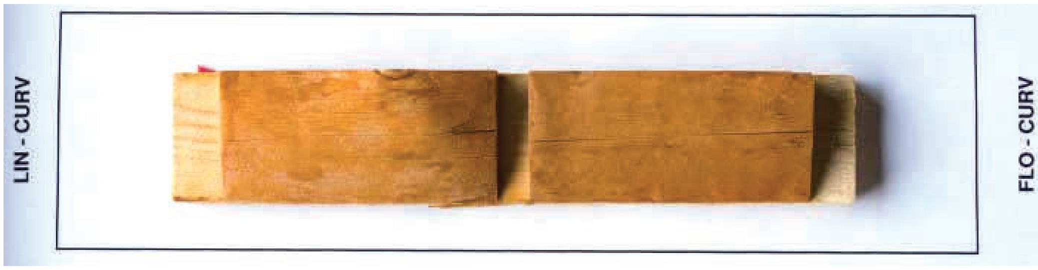
200 Hours

100 Hours

0 Hours (Pre-Weathering)

Sample Changes Over Time:

Curved Samples (Linseed Oil (Top) and Flood CWF UV-5 (Bottom)):



800 Hours (Post-Weathering, Out of Brackets)

800 Hours (Post-Weathering)

700 Hours

600 Hours

500 Hours

Sample Changes Over Time:

Curved Samples (Paraffin and Mineral Spirits (Top) & DEFY Extreme (Bottom):

400 Hours

300 Hours

200 Hours

100 Hours

0 Hours (Pre-Weathering)

Sample Changes Over Time:

Curved Samples (Paraffin and Mineral Spirits (Top) & DEFY Extreme (Bottom):

800 Hours (Post-Weathering, Out of Brackets)

800 Hours (Post-Weathering)

700 Hours

600 Hours

500 Hours

Sample Changes Over Time:

Curved Samples (Armstrong's Wood Stain (Top) & TWP 1500 (Bottom):

400 Hours

300 Hours

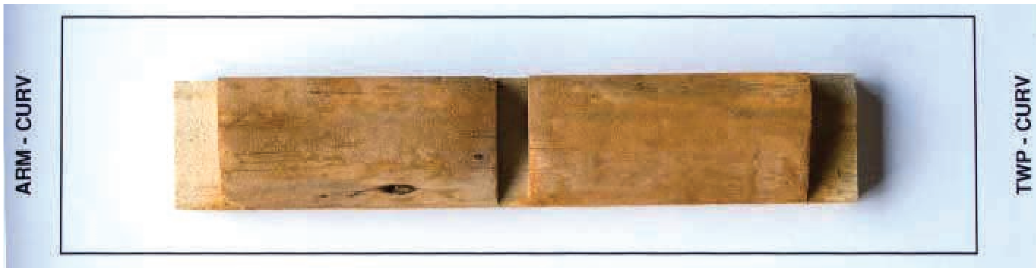
200 Hours

100 Hours

0 Hours (Pre-Weathering)

Sample Changes Over Time:

Curved Samples (Armstrong's Wood Stain (Top) & TWP 1500 (Bottom):



800 Hours (Post-Weathering, Out of Brackets)

800 Hours (Post-Weathering)

700 Hours

600 Hours

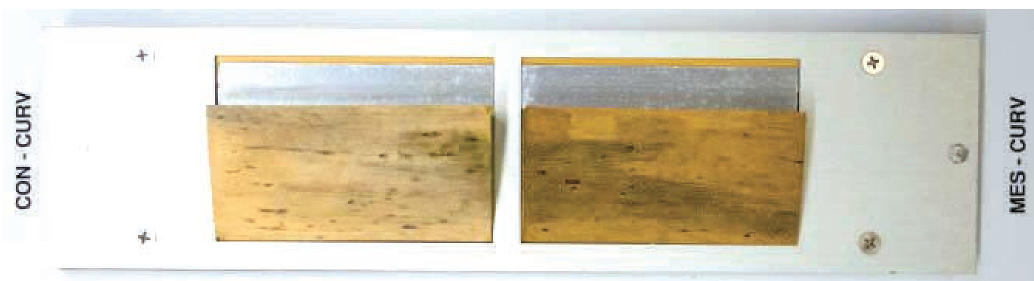
500 Hours

Sample Changes Over Time:

Curved Samples (Control (Top) & Messmer's UV Plus (Bottom):

400 Hours

300 Hours



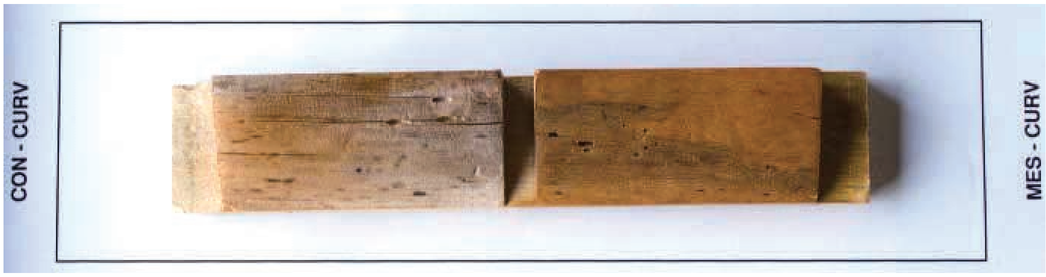
200 Hours

100 Hours

0 Hours (Pre-Weathering)

Sample Changes Over Time:

Curved Samples (Control (Top) & Messmer's UV Plus (Bottom):



800 Hours (Post-Weathering, Out of Brackets)

800 Hours (Post-Weathering)

700 Hours

600 Hours

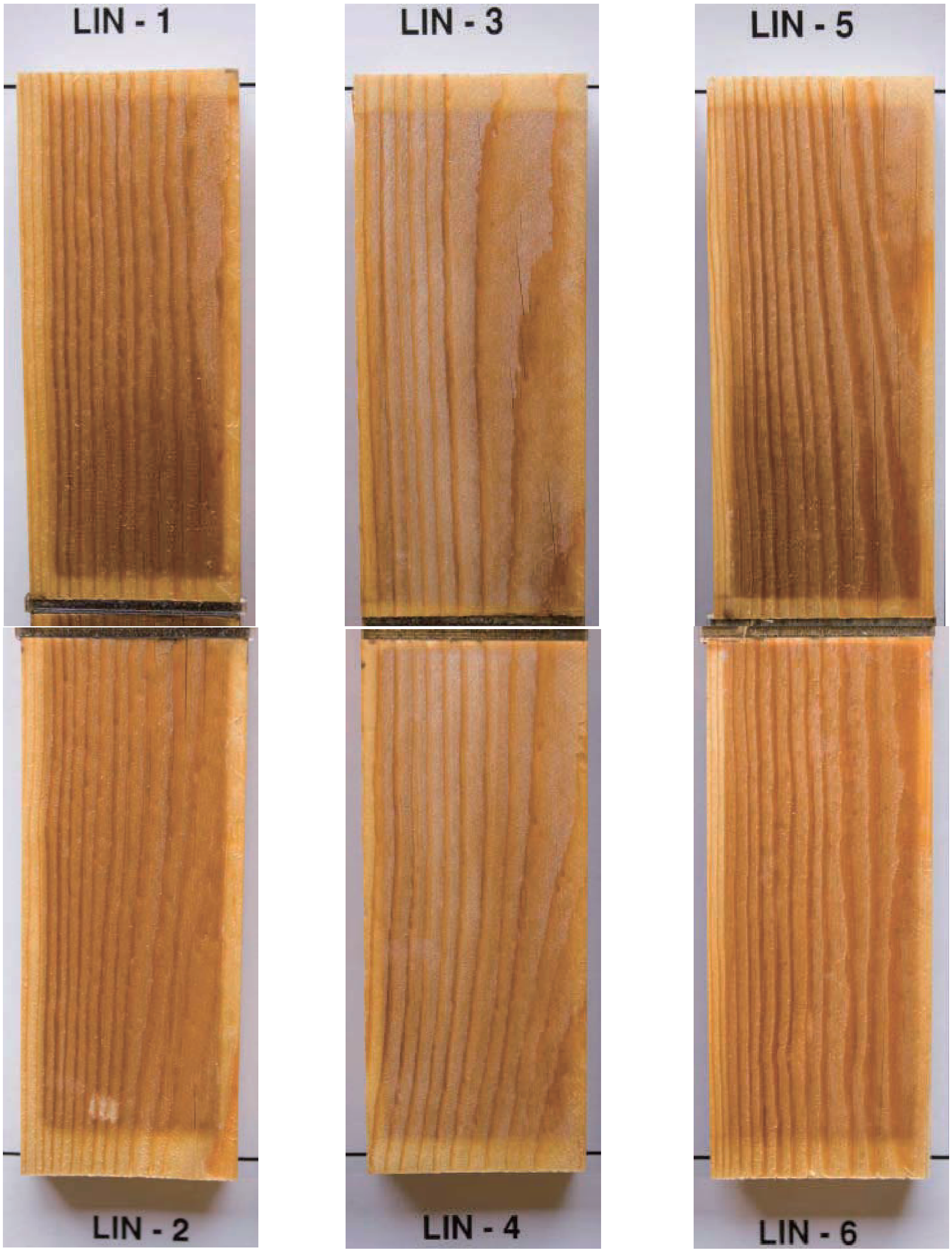
500 Hours

Detail photographs of each sample post-weathering:

Control:

Detail photographs of each sample post-weathering:

Allbäck Boiled Organic Linseed Oil:



Detail photographs of each sample post-weathering:

Paraffin and Mineral Spirits:

Detail photographs of each sample post-weathering:

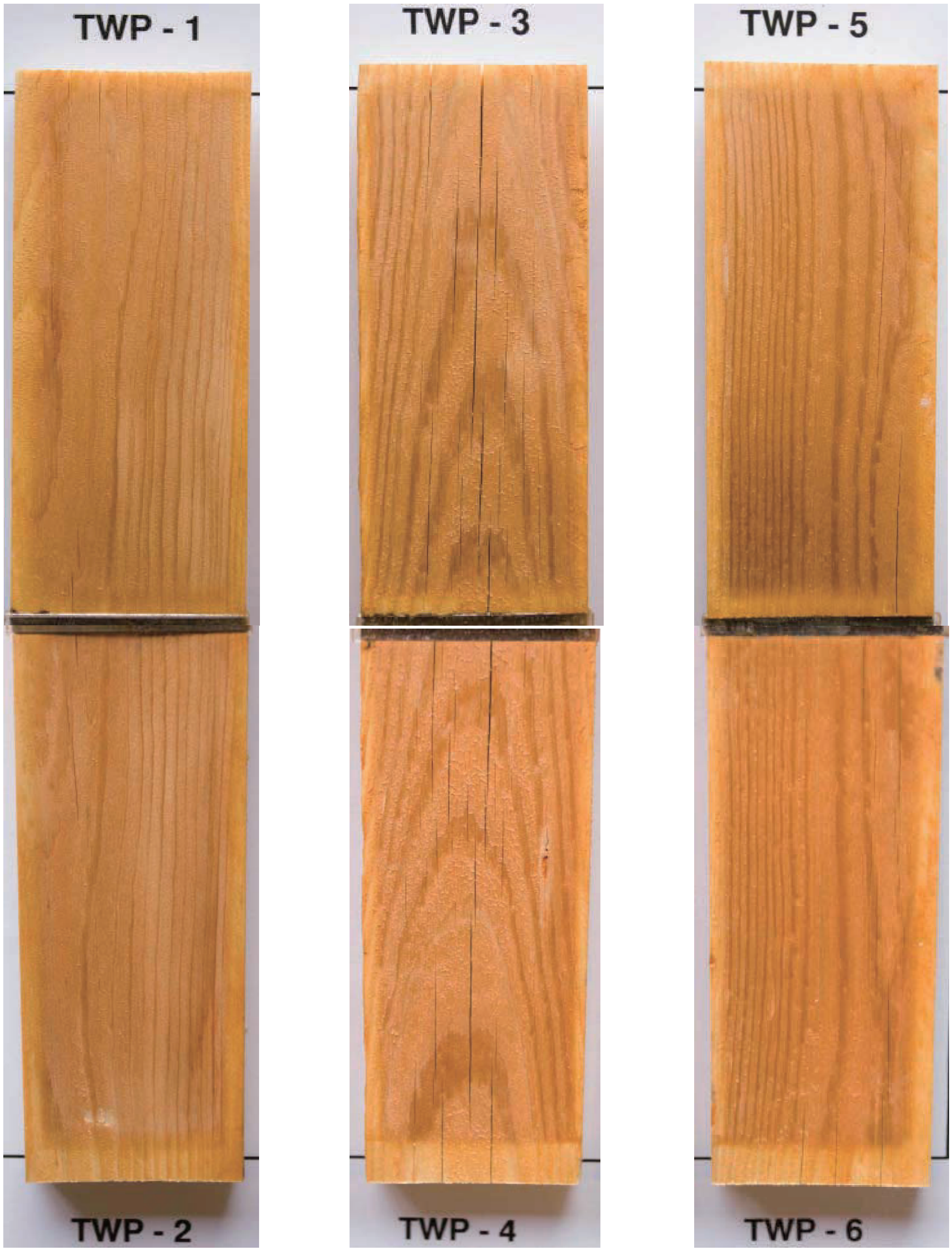
DEFY Extreme Exterior Clear Wood Stain:

Detail photographs of each sample post-weathering:

Armstrong's Wood Stain for Decks (Natural Tone):

Detail photographs of each sample post-weathering:

TWP 1500 Natural Stain (Natural Tone):



Detail photographs of each sample post-weathering:

Flood CWF UV-5 Penetrating Wood Finish for Fences, Decks, and Siding (Natural Tone (Clear)):

Detail photographs of each sample post-weathering:

Messmer's U.V. Plus Exterior Wood Finish (Natural):

Detail photographs of each sample post-weathering:

Curved:

Linseed Oil

Paraffin and Mineral Spirits

Armstrong's Wood Stain

Control

Flood CWF UV-5

DEFY Extreme

TWP 1500

Messmer's UV Plus

Appendix G - T-test Calculations

Sample Weights Before and After Treatment:

CONTROL

t-Test: Two-Sample Assuming Equal Variances

	72.77	72.77
Mean	72.365	72.365
Variance	8.77805	8.77805
Observations	2	2
Pooled Variance	8.77805	
Hypothesized Mean Difference	0	
df	2	
t Stat	0	
P(T<=t) one-tail	0.5	
t Critical one-tail	2.91998558	
P(T<=t) two-tail	1	
t Critical two-tail	4.30265273	

LINSEED

t-Test: Paired Two Sample for Means

	73.09	74.93
Mean	69.42	71.08
Variance	101.9592	87.9138
Observations	2	2
Pearson Correlation	1	
Hypothesized Mean Difference	0	
df	1	
t Stat	-3.25490196	
P(T<=t) one-tail	0.094880398	
t Critical one-tail	6.313751515	
P(T<=t) two-tail	0.189760796	
t Critical two-tail	12.70620474	

PARAFFIN

t-Test: Paired Two Sample for Means

	76.41	77.18
Mean	70.245	70.935
Variance	82.56125	70.21125
Observations	2	2
Pearson Correlation	1	
Hypothesized Mean Difference	0	
df	1	
t Stat	-1.38	
P(T<=t) one-tail	0.199602791	
t Critical one-tail	6.313751515	
P(T<=t) two-tail	0.399205582	
t Critical two-tail	12.70620474	

DEFY

t-Test: Paired Two Sample for Means

	76.87	78.22
Mean	63.66	64.86
Variance	19.0962	14.6882
Observations	2	2
Pearson Correlation	1	
Hypothesized Mean Difference	0	
df	1	
t Stat	-3.15789474	
P(T<=t) one-tail	0.097618104	
t Critical one-tail	6.313751515	
P(T<=t) two-tail	0.195236209	
t Critical two-tail	12.70620474	

ARMSTRONG

t-Test: Paired Two Sample for Means

	74.3	76.02
Mean	76.205	78.345
Variance	17.11125	16.07445
Observations	2	2
Pearson Correlation	1	
Hypothesized Mean Difference	0	
df	1	
t Stat	-23.7777778	
P(T<=t) one-tail	0.01337898	
t Critical one-tail	6.313751515	
P(T<=t) two-tail	0.02675796	
t Critical two-tail	12.70620474	

TWP

t-Test: Paired Two Sample for Means

	58.01	59.27
Mean	73.42	74.23
Variance	0.3362	0.2592
Observations	2	2
Pearson Correlation	1	
Hypothesized Mean Difference	0	
df	1	
t Stat	-16.2	
P(T<=t) one-tail	0.019623859	
t Critical one-tail	6.313751515	
P(T<=t) two-tail	0.039247718	
t Critical two-tail	12.70620474	

Sample Weights Before and After Treatment:

FLOOD

t-Test: Paired Two Sample for Means

	76.11	77.21
Mean	75.75	76.495
Variance	16.9362	15.40125
Observations	2	2
Pearson Correlation	1	
Hypothesized Mean Difference	0	
df	1	
t Stat	-5.51851852	
P(T<=t) one-tail	0.057061132	
t Critical one-tail	6.313751515	
P(T<=t) two-tail	0.114122264	
t Critical two-tail	12.70620474	

MESSMERS

t-Test: Paired Two Sample for Means

	68.68	69.56
Mean	67.31	68.49
Variance	0.6498	0.7442
Observations	2	2
Pearson Correlation	1	
Hypothesized Mean Difference	0	
df	1	
t Stat	-29.5	
P(T<=t) one-tail	0.010786036	
t Critical one-tail	6.313751515	
P(T<=t) two-tail	0.021572071	
t Critical two-tail	12.70620474	

CURVED

t-Test: Paired Two Sample for Means

	88.94	90.43
Mean	99.08333333	99.21
Variance	83.99903333	87.0807
Observations	3	3
Pearson Correlation	0.999993125	
Hypothesized Mean Difference	0	
df	2	
t Stat	-1.28980404	
P(T<=t) one-tail	0.163069721	
t Critical one-tail	2.91998558	
P(T<=t) two-tail	0.326139443	
t Critical two-tail	4.30265273	

Sample Weights Before and After Weathering:

CONTROL

t-Test: Paired Two Sample for Means

	72.77	*71.71*
Mean	72.365	70.815
Variance	8.77805	5.61125
Observations	2	2
Pearson Correlation	1	
Hypothesized Mean Difference	0	
df	1	
t Stat	3.69047619	
P(T<=t) one-tail	0.084229125	
t Critical one-tail	6.313751515	
P(T<=t) two-tail	0.168458251	
t Critical two-tail	12.70620474	

LINSEED

t-Test: Paired Two Sample for Means

	74.93	*73.3*
Mean	71.08	69.16
Variance	87.9138	84.7602
Observations	2	2
Pearson Correlation	1	
Hypothesized Mean Difference	0	
df	1	
t Stat	16	
P(T<=t) one-tail	0.019868524	
t Critical one-tail	6.313751515	
P(T<=t) two-tail	0.039737049	
t Critical two-tail	12.70620474	

PARAFFIN

t-Test: Paired Two Sample for Means

	77.18	*75.55*
Mean	70.935	69.01
Variance	70.21125	64.0712
Observations	2	2
Pearson Correlation	1	
Hypothesized Mean Difference	0	
df	1	
t Stat	7.264150943	
P(T<=t) one-tail	0.043545583	
t Critical one-tail	6.313751515	
P(T<=t) two-tail	0.087091166	
t Critical two-tail	12.70620474	

DEFY

t-Test: Paired Two Sample for Means

	78.22	*76.48*
Mean	64.86	63.21
Variance	14.6882	11.9072
Observations	2	2
Pearson Correlation	1	
Hypothesized Mean Difference	0	
df	1	
t Stat	6.111111111	
P(T<=t) one-tail	0.051629492	
t Critical one-tail	6.313751515	
P(T<=t) two-tail	0.103258984	
t Critical two-tail	12.70620474	

ARMSTRONG

t-Test: Paired Two Sample for Means

	76.02	*74.16*
Mean	78.345	76.865
Variance	16.07445	16.99445
Observations	2	2
Pearson Correlation	1	
Hypothesized Mean Difference	0	
df	1	
t Stat	18.5	
P(T<=t) one-tail	0.017189211	
t Critical one-tail	6.313751515	

TWP

t-Test: Two-Sample Assuming Equal Variances

	59.27	*57.47*
Mean	74.23	72.44
Variance	0.2592	0.2592
Observations	2	2
Pooled Variance	0.2592	
Hypothesized Mean Difference	0	
df	2	
t Stat	3.515892051	
P(T<=t) one-tail	0.036119964	
t Critical one-tail	2.91998558	

Sample Weights Before and After Weathering:

FLOOD

t-Test: Paired Two Sample for Means

	77.21	*75.58*
Mean	76.495	74.49
Variance	15.40125	16.7042
Observations	2	2
Pearson Correlation	1	
Hypothesized Mean Difference	0	
df	1	
t Stat	17.43478261	
P(T<=t) one-tail	0.018237194	
t Critical one-tail	6.313751515	
P(T<=t) two-tail	0.036474388	
t Critical two-tail	12.70620474	

MESSMERS

t-Test: Paired Two Sample for Means

	69.56	*67.82*
Mean	68.49	66.78
Variance	0.7442	0.5832
Observations	2	2
Pearson Correlation	1	
Hypothesized Mean Difference	0	
df	1	
t Stat	24.42857143	
P(T<=t) one-tail	0.013022958	
t Critical one-tail	6.313751515	
P(T<=t) two-tail	0.026045916	
t Critical two-tail	12.70620474	

CURVED

t-Test: Paired Two Sample for Means

	90.43	*90.3*
Mean	99.21	98.79333333
Variance	87.0807	92.15223333
Observations	3	3
Pearson Correlation	0.999252251	
Hypothesized Mean Difference	0	
df	2	
t Stat	1.591098456	
P(T<=t) one-tail	0.126284124	
t Critical one-tail	2.91998558	
P(T<=t) two-tail	0.252568248	
t Critical two-tail	4.30265273	

Contact Angles on Sample Surfaces Before and After Weathering:

CONTROL
left:

t-Test: Paired Two Sample for Means

	97.9	*135.9*
Mean	94.86	125.68
Variance	93.063	425.632
Observations	5	5
Pearson Correlation	0.504858467	
Hypothesized Mean Difference	0	
df	4	
t Stat	-3.86619488	
P(T<=t) one-tail	0.009025905	
t Critical one-tail	2.131846786	
P(T<=t) two-tail	0.01805181	
t Critical two-tail	2.776445105	

right:

t-Test: Paired Two Sample for Means

	87.6	*132.1*
Mean	91	118.14
Variance	78.015	1206.673
Observations	5	5
Pearson Correlation	0.761024049	
Hypothesized Mean Difference	0	
df	4	
t Stat	-2.12226546	
P(T<=t) one-tail	0.050541944	
t Critical one-tail	2.131846786	
P(T<=t) two-tail	0.101083887	
t Critical two-tail	2.776445105	

LINSEED
left:

t-Test: Paired Two Sample for Means

	84.9	*85*
Mean	80.58	72.9
Variance	35.807	39.535
Observations	5	5
Pearson Correlation	0.382725723	
Hypothesized Mean Difference	0	
df	4	
t Stat	2.51723465	
P(T<=t) one-tail	0.032774829	
t Critical one-tail	2.131846786	
P(T<=t) two-tail	0.065549657	
t Critical two-tail	2.776445105	

right:

t-Test: Paired Two Sample for Means

	84.9	*82.1*
Mean	78	76.08
Variance	48.96	53.842
Observations	5	5
Pearson Correlation	0.835118605	
Hypothesized Mean Difference	0	
df	4	
t Stat	1.039829778	
P(T<=t) one-tail	0.178569853	
t Critical one-tail	2.131846786	
P(T<=t) two-tail	0.357139706	
t Critical two-tail	2.776445105	

PARAFFIN
left:

t-Test: Paired Two Sample for Means

	77.9	*180*
Mean	79.2	143
Variance	104.685	1813.865
Observations	5	5
Pearson Correlation	-5.7371E-06	
Hypothesized Mean Difference	0	
df	4	
t Stat	-3.25700597	
P(T<=t) one-tail	0.015584385	
t Critical one-tail	2.131846786	
P(T<=t) two-tail	0.031168771	
t Critical two-tail	2.776445105	

right:

t-Test: Paired Two Sample for Means

	80.4	*180*
Mean	78.5	135.24
Variance	101.445	2168.613
Observations	5	5
Pearson Correlation	0.48020815	
Hypothesized Mean Difference	0	
df	4	
t Stat	-2.97432075	
P(T<=t) one-tail	0.020484273	
t Critical one-tail	2.131846786	
P(T<=t) two-tail	0.040968547	
t Critical two-tail	2.776445105	

Contact Angles on Sample Surfaces Before and After Weathering:

DEFY

left:

t-Test: Paired Two Sample for Means

	107.8	*86.2*
Mean	70.12	80.8
Variance	208.537	21.085
Observations	5	5
Pearson Correlation	-0.2375588	
Hypothesized Mean Difference	0	
df	4	
t Stat	-1.47785003	
P(T<=t) one-tail	0.106758232	
t Critical one-tail	2.131846786	
P(T<=t) two-tail	0.213516463	
t Critical two-tail	2.776445105	

right:

t-Test: Paired Two Sample for Means

	99.9	*82.1*
Mean	70.44	82.64
Variance	259.688	13.543
Observations	5	5
Pearson Correlation	-0.56626951	
Hypothesized Mean Difference	0	
df	4	
t Stat	-1.47860866	
P(T<=t) one-tail	0.106662549	
t Critical one-tail	2.131846786	
P(T<=t) two-tail	0.213325097	
t Critical two-tail	2.776445105	

ARMSTRONG

left:

t-Test: Paired Two Sample for Means

	63	*76.6*
Mean	70	76.64
Variance	22.205	52.923
Observations	5	5
Pearson Correlation	0.218126688	
Hypothesized Mean Difference	0	
df	4	
t Stat	-1.91404546	
P(T<=t) one-tail	0.064073615	
t Critical one-tail	2.131846786	
P(T<=t) two-tail	0.12814723	
t Critical two-tail	2.776445105	

right:

t-Test: Paired Two Sample for Means

	66.4	*73.6*
Mean	69.36	76.34
Variance	18.653	62.403
Observations	5	5
Pearson Correlation	-0.0943944	
Hypothesized Mean Difference	0	
df	4	
t Stat	-1.66856774	
P(T<=t) one-tail	0.085263838	
t Critical one-tail	2.131846786	
P(T<=t) two-tail	0.170527676	
t Critical two-tail	2.776445105	

TWP

left:

t-Test: Paired Two Sample for Means

	67.4	*71.2*
Mean	61.82	62.3
Variance	73.427	14.195
Observations	5	5
Pearson Correlation	0.337002641	
Hypothesized Mean Difference	0	
df	4	
t Stat	-0.13225399	
P(T<=t) one-tail	0.450584652	
t Critical one-tail	2.131846786	
P(T<=t) two-tail	0.901169304	
t Critical two-tail	2.776445105	

right:

t-Test: Paired Two Sample for Means

	69	*73.3*
Mean	62.48	65
Variance	73.502	33.155
Observations	5	5
Pearson Correlation	0.174868866	
Hypothesized Mean Difference	0	
df	4	
t Stat	-0.59598622	
P(T<=t) one-tail	0.291635695	
t Critical one-tail	2.131846786	
P(T<=t) two-tail	0.583271389	
t Critical two-tail	2.776445105	

Contact Angles on Sample Surfaces Before and After Weathering:

FLOOD

left:

t-Test: Paired Two Sample for Means

	74.2	*92.4*
Mean	83.66	99.06
Variance	53.233	24.623
Observations	5	5
Pearson Correlation	-0.6782193	
Hypothesized Mean Difference	0	
df	4	
t Stat	-3.05607293	
P(T<=t) one-tail	0.018901595	
t Critical one-tail	2.131846786	
P(T<=t) two-tail	0.03780319	
t Critical two-tail	2.776445105	

right:

t-Test: Paired Two Sample for Means

	74.4	*109.9*
Mean	85.38	99.62
Variance	54.547	22.417
Observations	5	5
Pearson Correlation	-0.68224702	
Hypothesized Mean Difference	0	
df	4	
t Stat	-2.85167533	
P(T<=t) one-tail	0.023158648	
t Critical one-tail	2.131846786	
P(T<=t) two-tail	0.046317296	
t Critical two-tail	2.776445105	

MESSMERS

left:

t-Test: Paired Two Sample for Means

	81.8	*71.5*
Mean	78.12	72.64
Variance	82.597	52.693
Observations	5	5
Pearson Correlation	0.301969748	
Hypothesized Mean Difference	0	
df	4	
t Stat	1.254250894	
P(T<=t) one-tail	0.139022474	
t Critical one-tail	2.131846786	
P(T<=t) two-tail	0.278044948	
t Critical two-tail	2.776445105	

right:

t-Test: Paired Two Sample for Means

	80.3	*69.8*
Mean	76.86	74.84
Variance	55.558	110.123
Observations	5	5
Pearson Correlation	0.362789043	
Hypothesized Mean Difference	0	
df	4	
t Stat	0.432781413	
P(T<=t) one-tail	0.343743287	
t Critical one-tail	2.131846786	
P(T<=t) two-tail	0.687486574	
t Critical two-tail	2.776445105	

Index